NuFact15 : XVII International Workshop on Neutrino Factories and Future Neutrino Facilities

Recent results from the OPERA experiment

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CBPF Rio de Janeiro
10 – 15 August 2015

Outline

- ✓ Introduction
- ✓ The OPERA *detector*
- ✓ Data Analysis
- ✓ OPERA *latest news*

Discovery of ν_τ appearance in the CNGS neutrino beam with the OPERA experiment

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[arXiv:1507.01417]
submitted to PRL

JHEP

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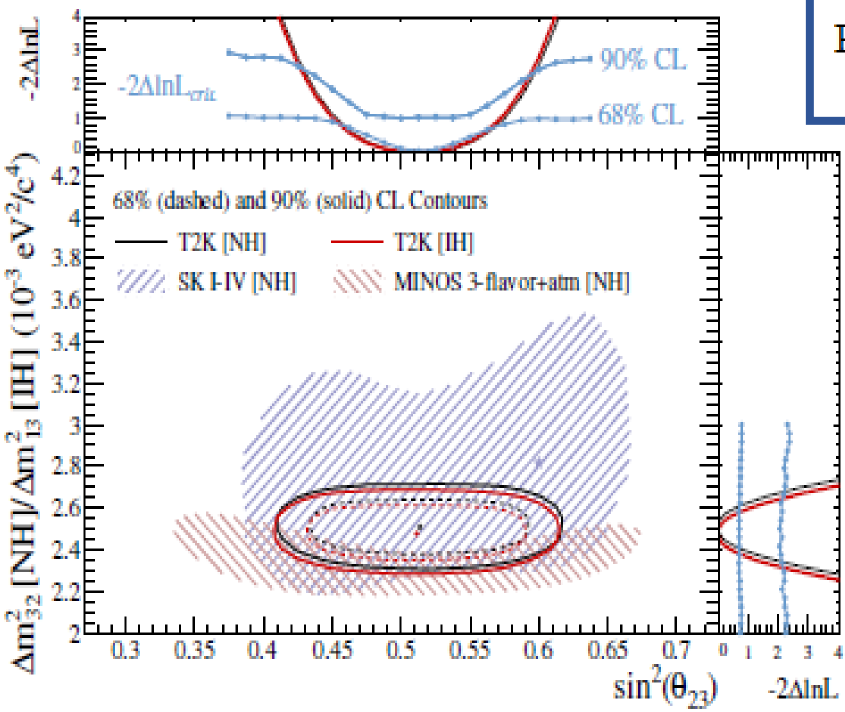
Limits on muon-neutrino to tau-neutrino oscillations induced by a sterile neutrino state obtained by OPERA at the CNGS beam

Introduction

- **<u>Super-K (1998), MACRO and Soudan-2</u>** : atmospheric neutrino anomaly explained as $\nu_\mu \to \nu_\tau$ oscillation
- **<u>K2K and MINOS (accelerator)</u>**: confirmation of the Super-K ν_μ disappearance signal



$$P(\nu_\mu \to \nu_\tau) \cong \sin^2(2\theta_{23})\cos^4(\theta_{13})\sin^2\left(\frac{1.27\Delta m^2_{32} L(\mathrm{Km})}{E(\mathrm{GeV})}\right)$$

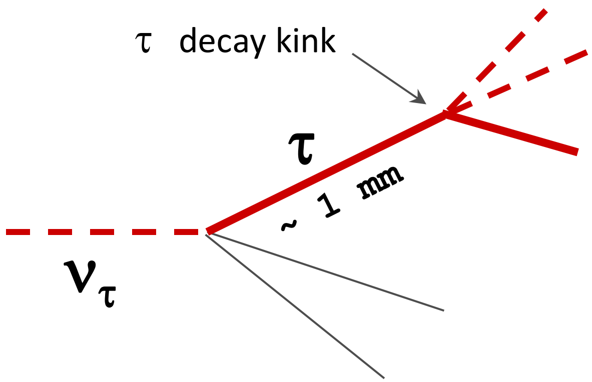
Opera was designed to confirm the oscillation searching the

ν_τ APPEARANCE SIGNAL

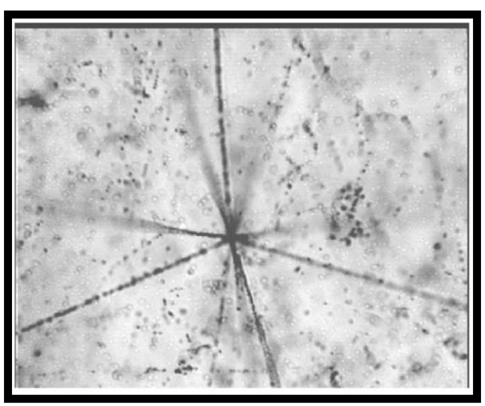
event-by-event basis in an artificial ν_μ beam

Challenge

Detection of ν_τ CC interaction by a full reconstruction of the primary interaction and observation of the τ lepton decay topologies.



Decay topology	B.R.
$\tau^- \rightarrow \mu^- \ \nu_\tau \nu_\mu$	17.4%
$\tau^- \rightarrow e^- \ \nu_\tau \ \nu_\varepsilon$	17.8%
$\tau^- \rightarrow h^- \ \nu_\tau \ n(\pi^o)$	49.5%
$\tau^- \rightarrow \pi^+\pi^-\pi^- \ \nu_\tau \ n(\pi^o)$	14.5%

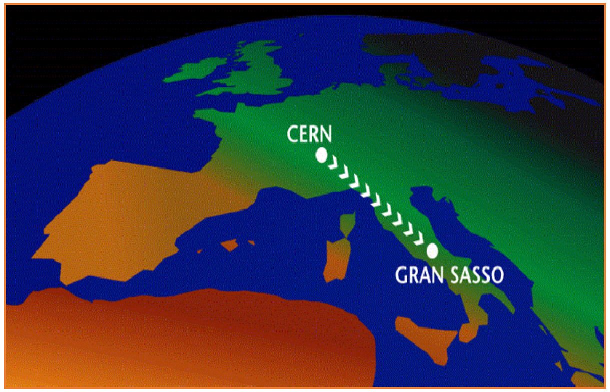


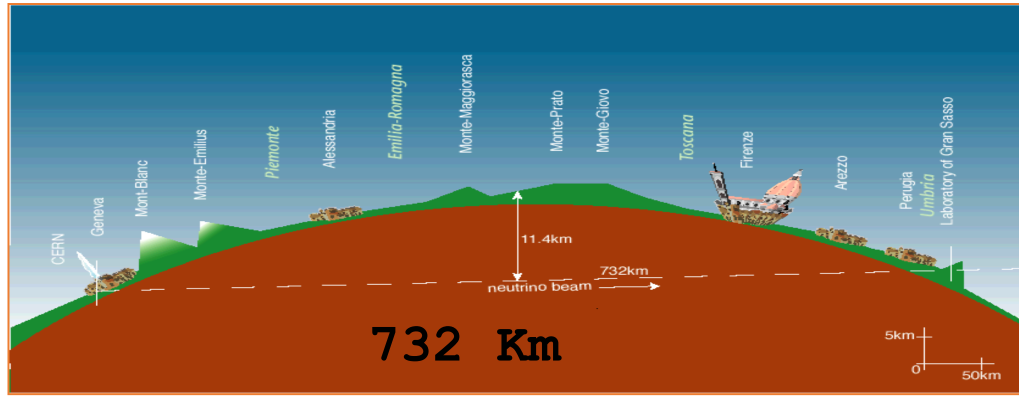
Nuclear emulsions + Lead (ECC) "active target"

- 3D particle reconstruction
- Sub-micron spatial resolution

High background rejection (S/B ~ 10)

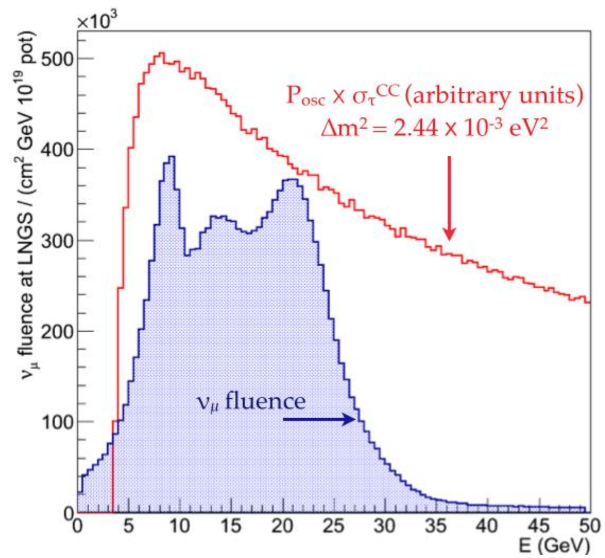
Oscillation Project with Emulsion tRacking Apparatus



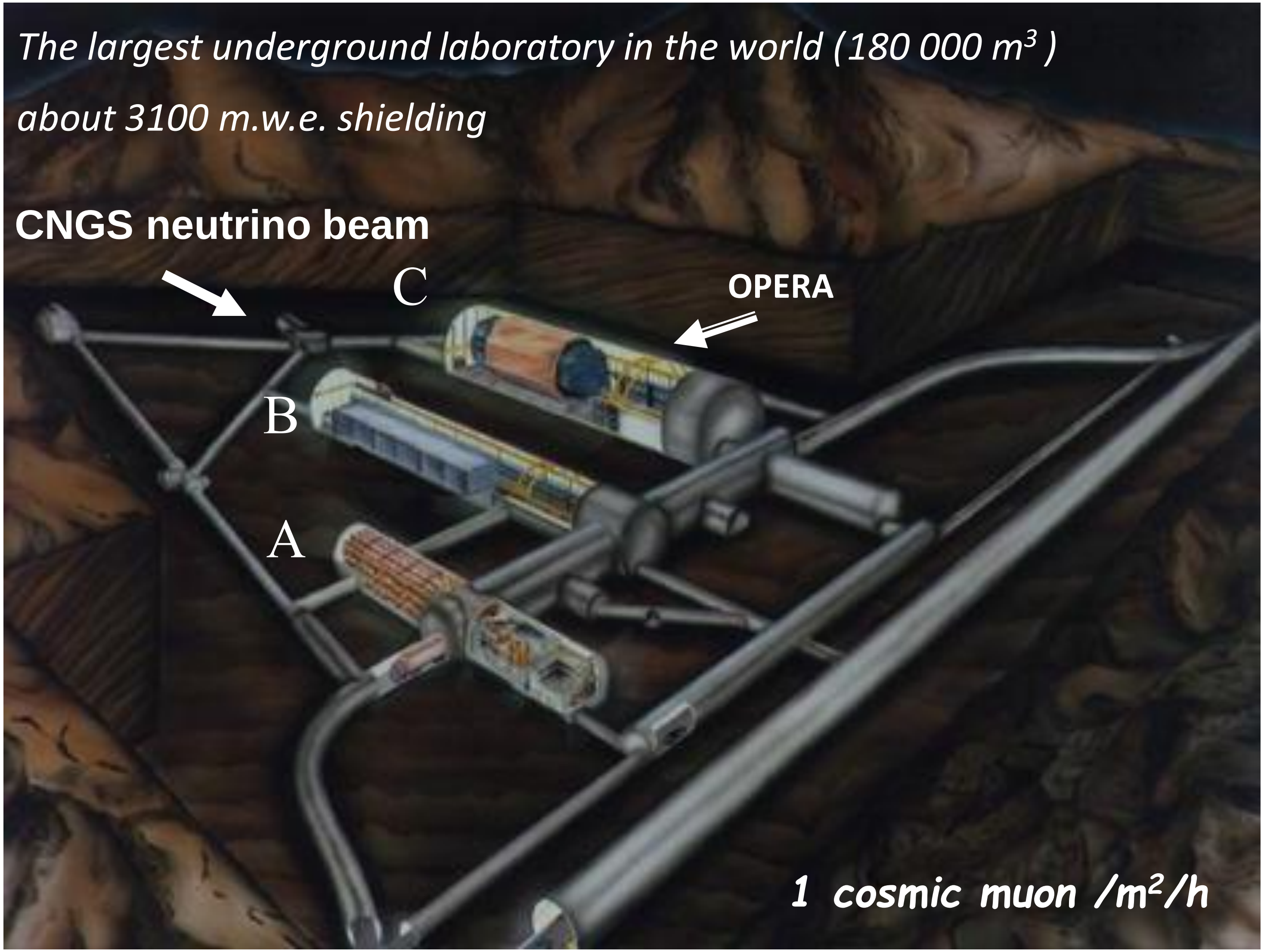


- Long baseline neutrino physics experiment
- ***CNGS*** quasi – pure wide band ν_μ beam, <L> = 732 km, <E> = 17 GeV optimized to maximize the number of ν_τ CC interactions

ν_μ(CC + NC)/year	~4700
ν_τ CC/year	~20
$(\nu_e + \bar{\nu}_e)/\ \nu_\mu$ CC	0.87%
$\bar{\nu}_\mu\ /\ \nu_\mu$ CC	2.1%
ν_τ prompt	negligible



LNGS – Gran Sasso National Lab



The OPERA collaboration

28 institutions - 140 physicists

http://operaweb.lngs.infn.it

Bari
Bologna
LNF Frascati
LNGS
Napoli
Padova
Roma
Salerno

IHE Brussels

Hamburg

IRB Zagreb

LAPP Annecy
IPHC Strasbourg

METU Ankara

LHEP Bern

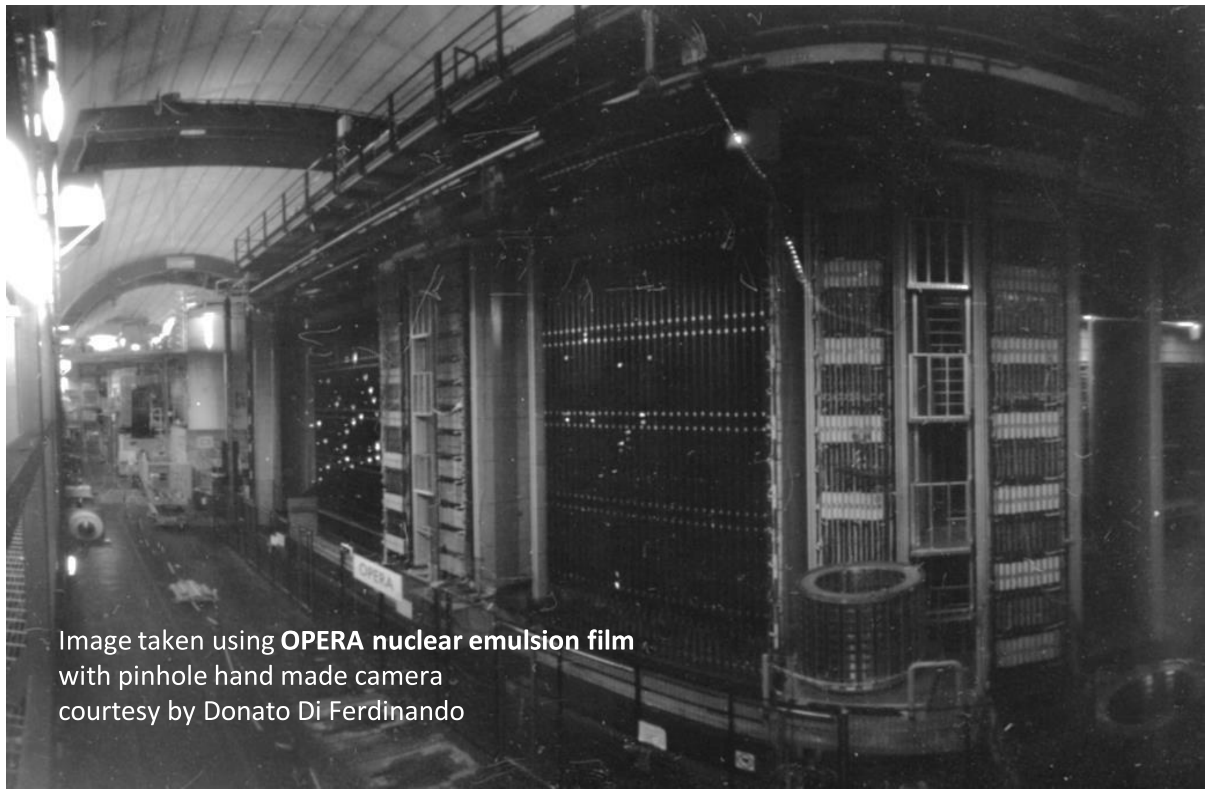


Image taken using **OPERA nuclear emulsion film** with pinhole hand made camera courtesy by Donato Di Ferdinando

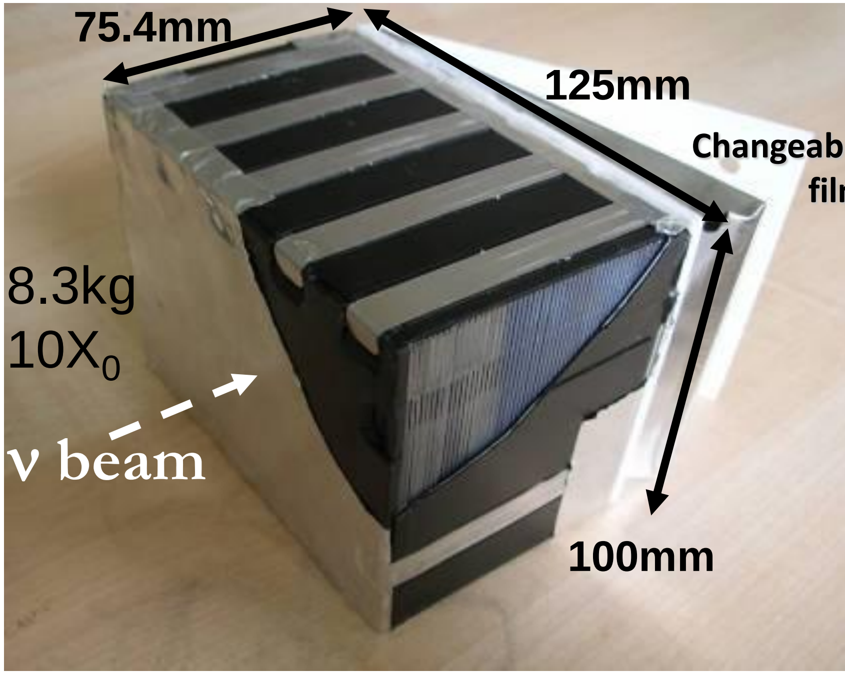
Technion Haifa

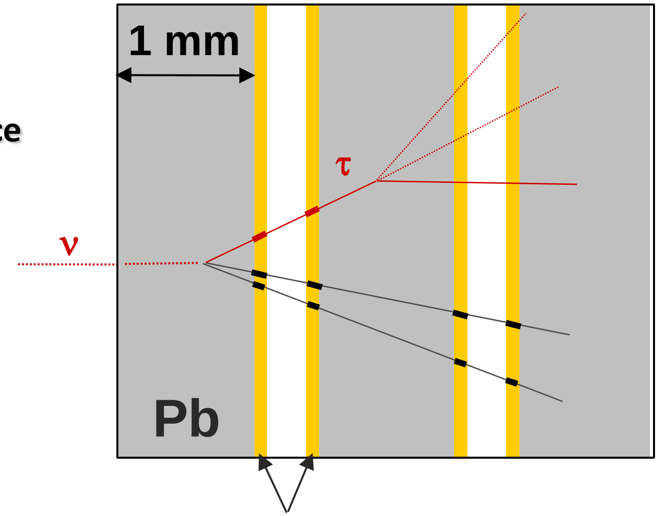
Jinjiu

Aichi
Toho
Kobe
Nagoya
NIhon

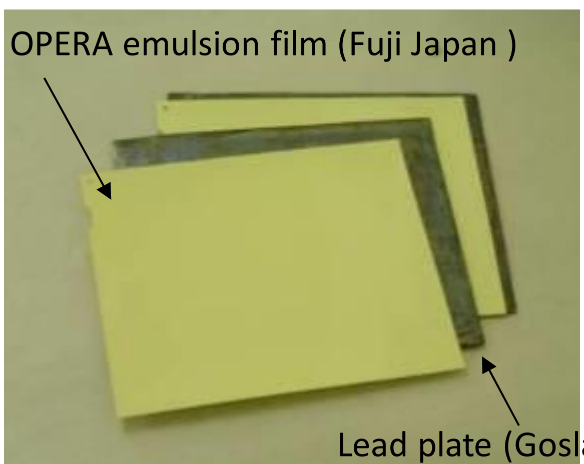
INR Moscow
LPI Moscow
SINP MSU Moscow
JINR Dubna

ECC target brick





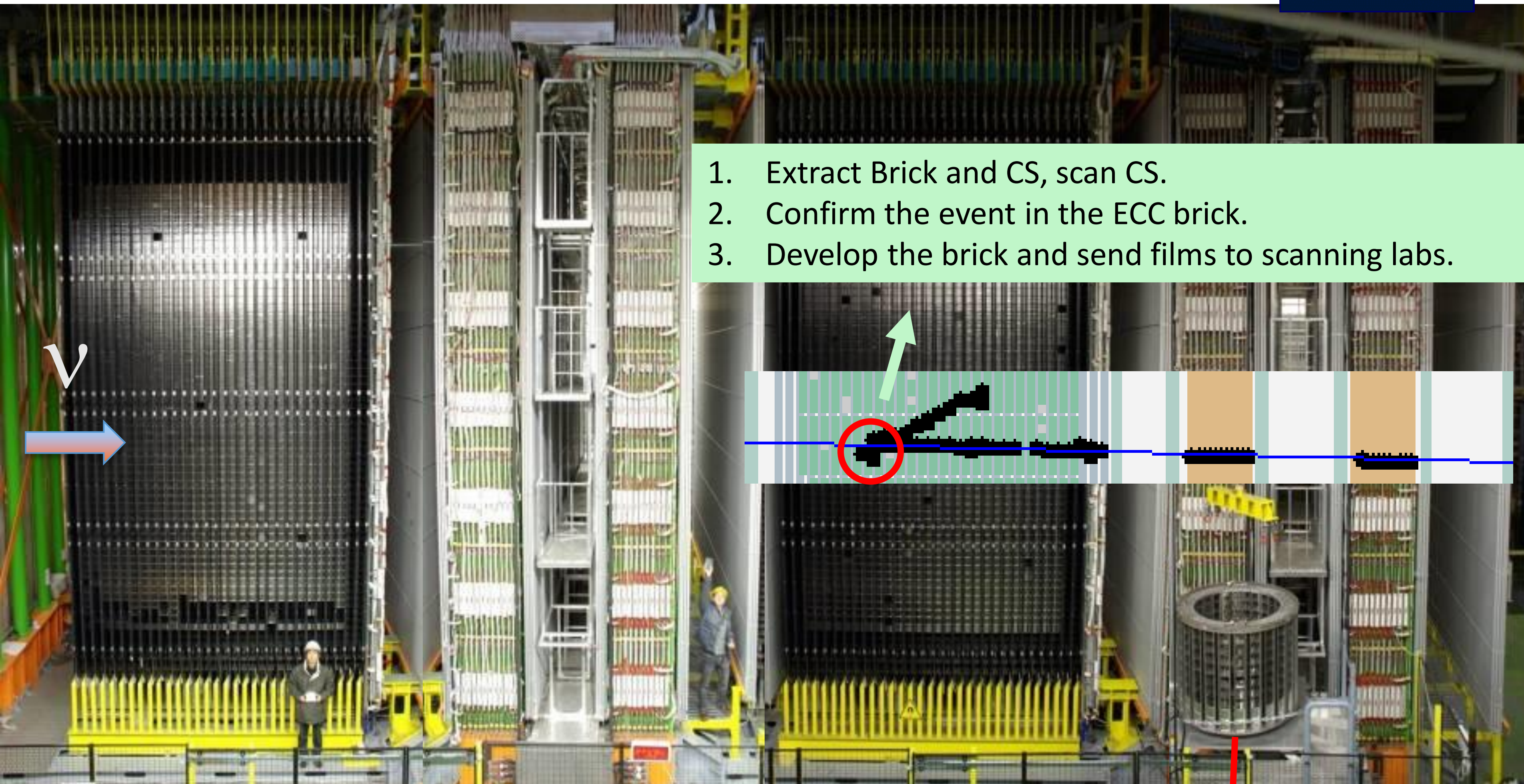
2 emulsion layers (42 μm thick) poured on a 200 μm plastic base



57 emulsion films + 2 CS interface sheet *Ref: **NIM A556 (2006) 80-86***

56 × 1 mm Pb (lead + 0.04 % Ca) plates *Ref: **JINST 3 P07002 (2008)***

SM1 SM2



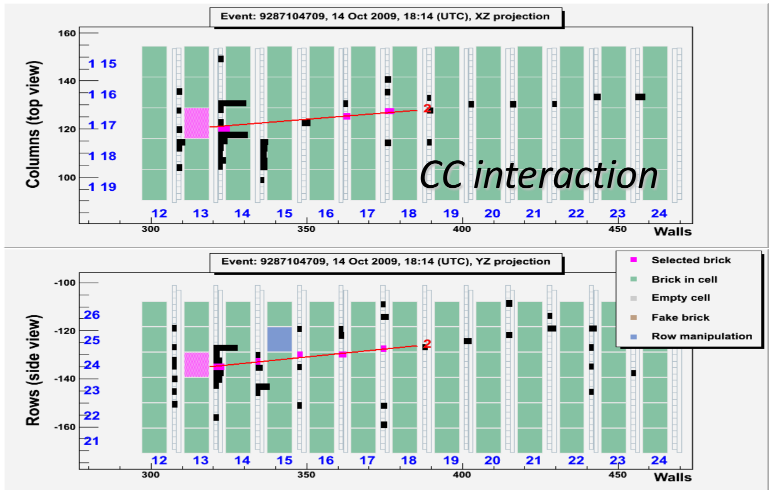
Target area : (ECC + CS + planes of scintillator strips)

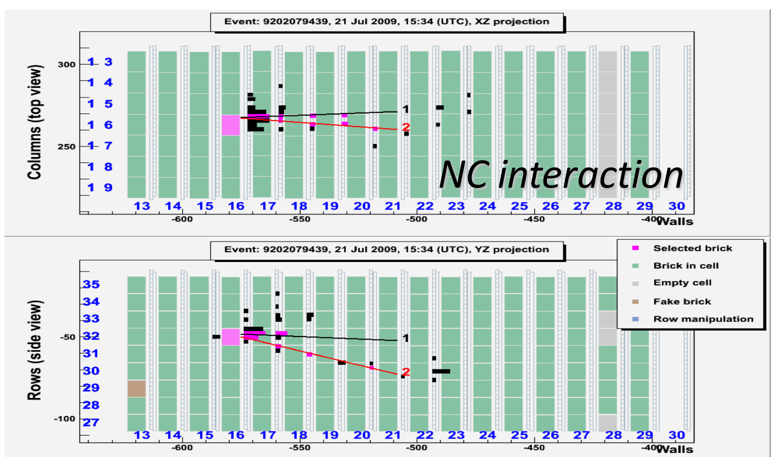
~ 150.000 bricks in total.
1.25 kt mass

Muon spectrometer (Magnet+RPC+PT)

Brick Manipulator System

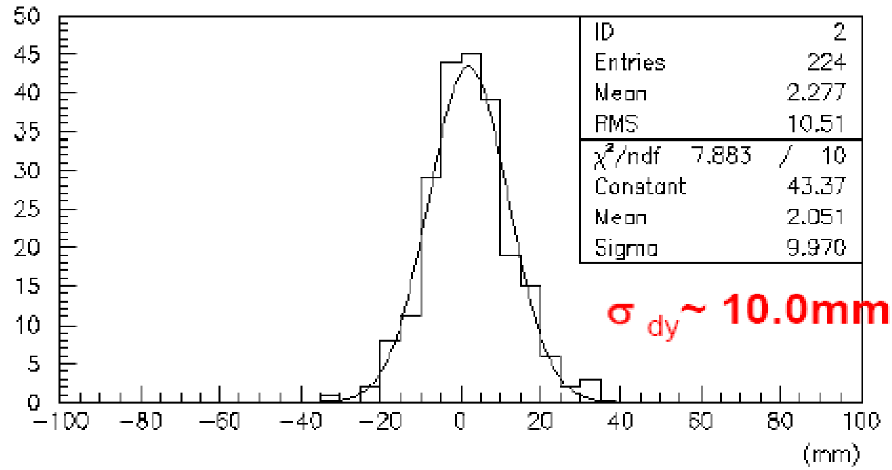
CS interface films scanning



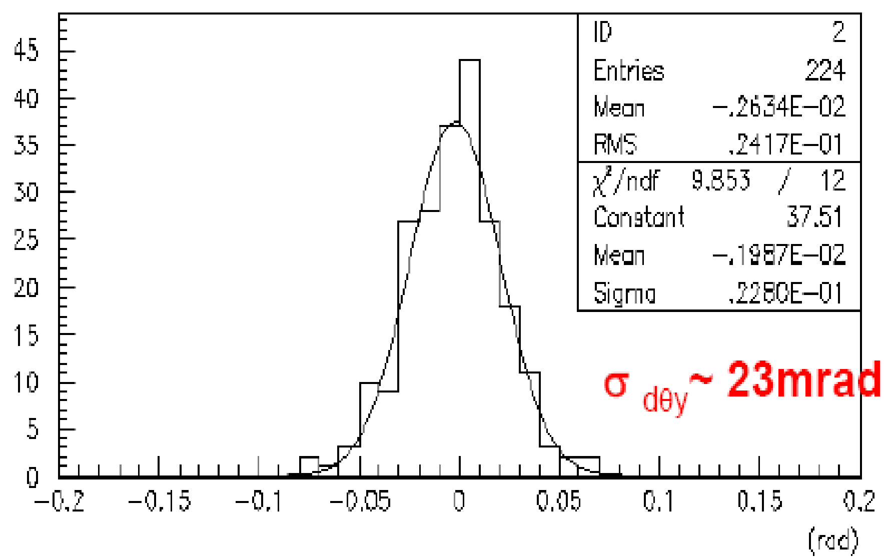


Ref: ***JINST 3 P07005 (2008)***

Interface emulsion films: high signal/noise ratio for event trigger and scanning time reduction



Position accuracy of the electronic predictions

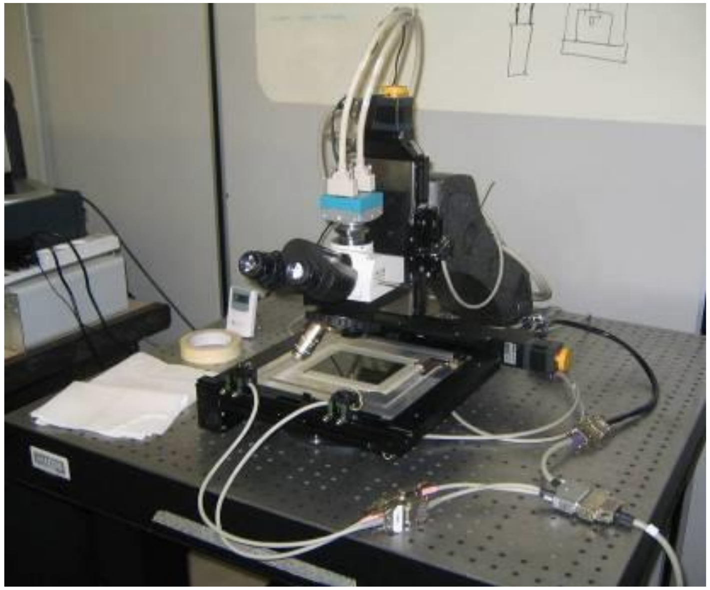


Angular accuracy of the electronic predictions

Emulsion film scanning

EU: ESS (European Scanning System)

Japan: SUTS (Super Ultra Track Selector)



- Scanning speed/system: 20cm^2/h
- Customized commercial optics and mechanics
- Asynchronous DAQ software

- Scanning speed/system: 75cm^2/h
- High speed CCD camera (3 kHz), Piezo-controlled objective lens
- FPGA Hard-coded algorithms

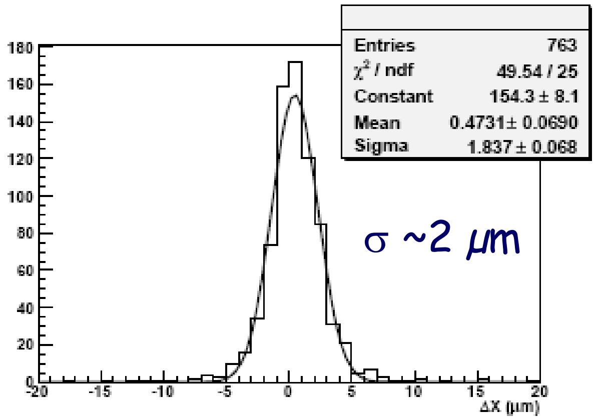
<u>Both systems have:</u>

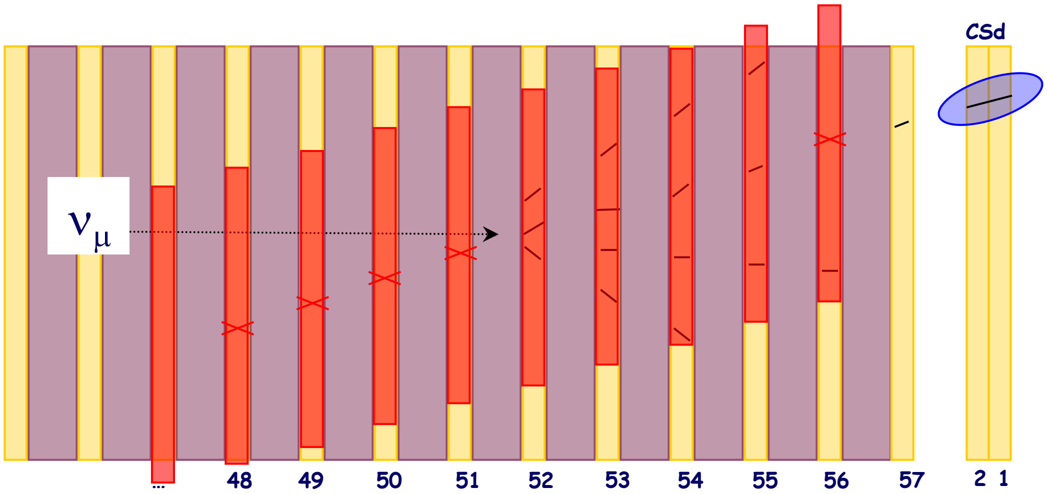
- ~ 0.3 μm spatial resolution
- ~ 2 mrad angular resolution
- ~ 95% detection efficiency on a single emulsion film

Interaction Vertex finding

Track follow-up film by film:

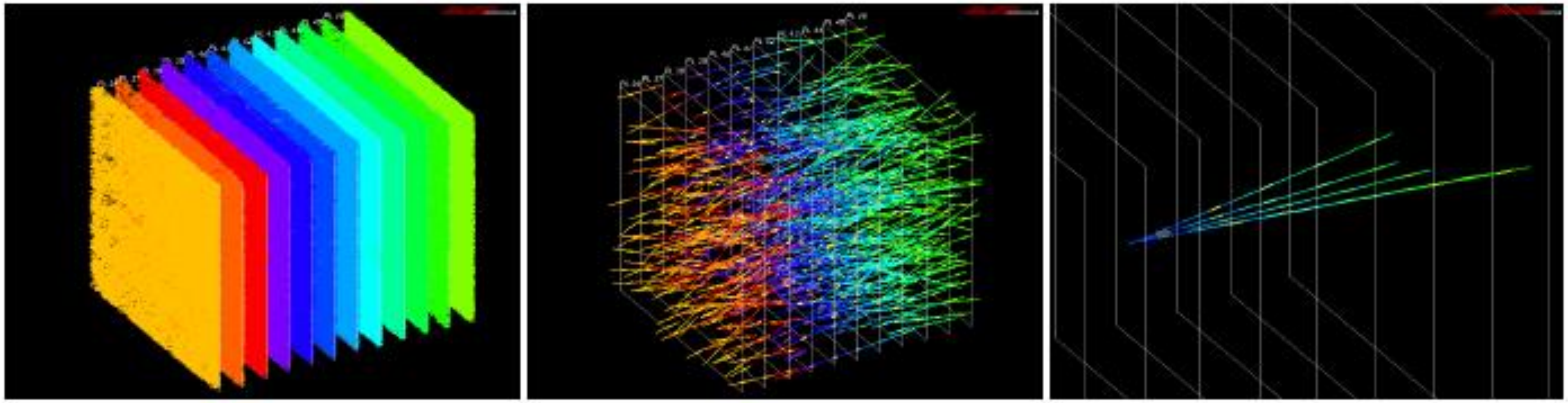
- alignment using cosmic ray tracks
- definition of the stopping point





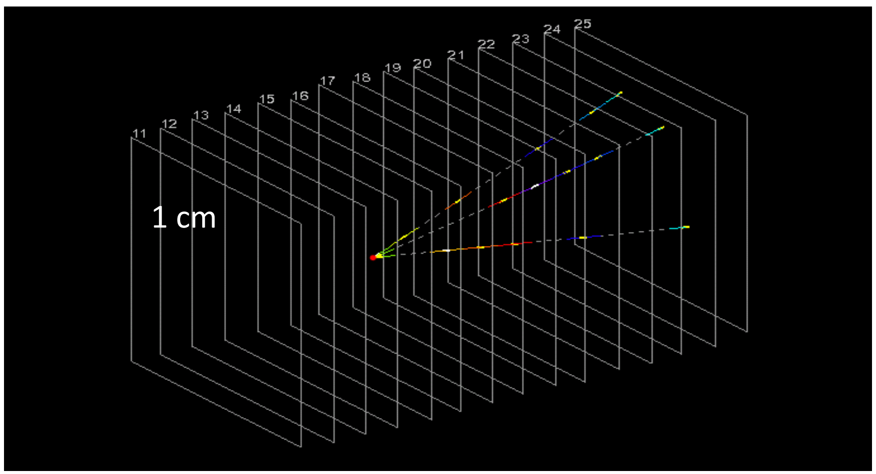
Ref. JINST 4 (2009) P06020

Volume scanning (~2 cm^3) around the stopping point



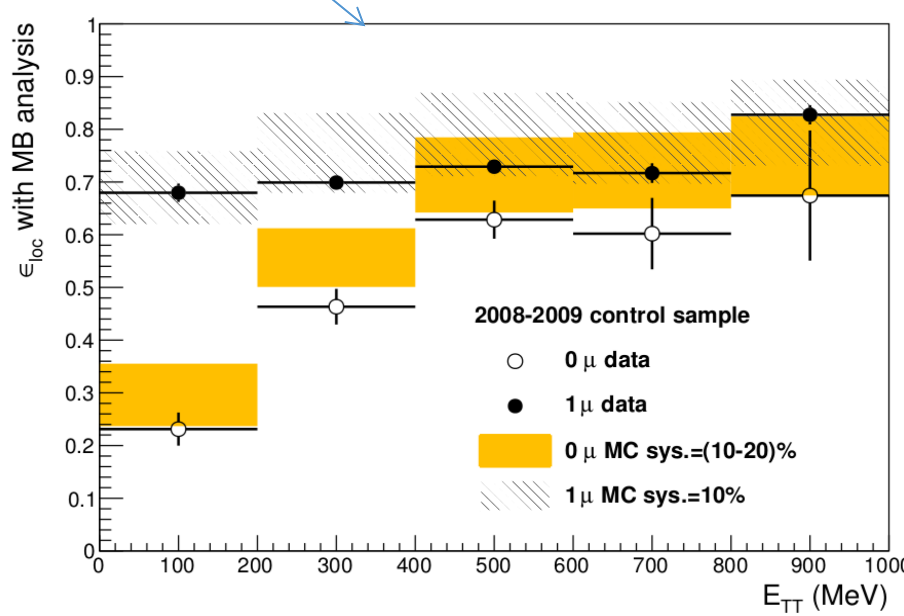
Location efficiency evaluation

The complete location procedure (electronic data followed by emulsion analysis) was simulated for efficiency evaluation.



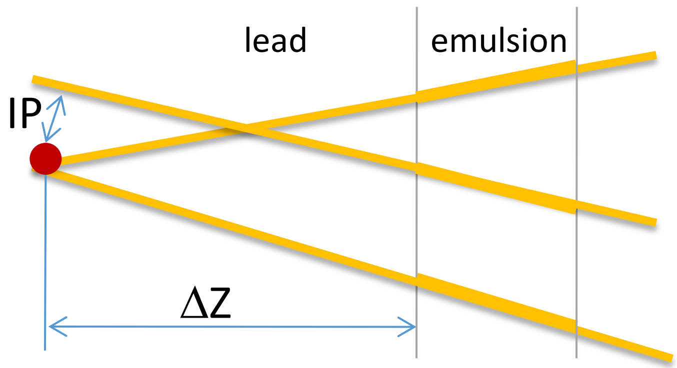
Data-Monte Carlo comparison of the **location efficiency** as a function of the visible energy in the target scintillators

[JHEP 11 (2013) 036]



The **predictions for the τ signal** and **backgrounds** are computed using the **efficiencies** derived from the observed 0μ–like (NC) and 1μ-like (CC) samples

Decay search procedure

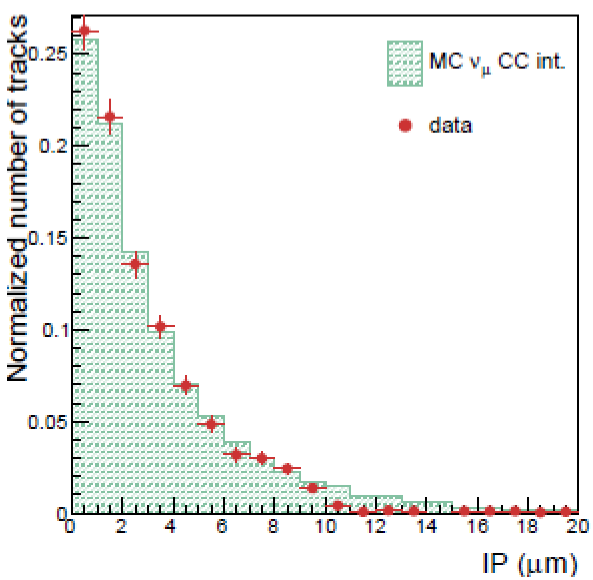


The IP evaluation is a crucial point in order to detect and reconstruct decay topologies

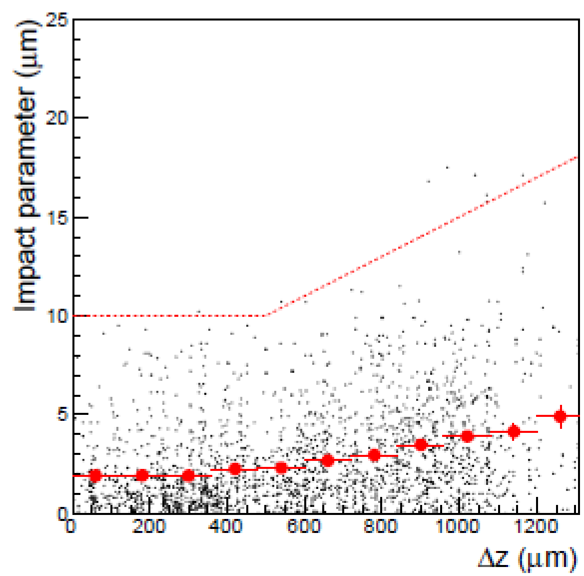
Each track is associated to the primary vertex only if

IP < 10 µm $\Delta Z < 500$ µm

IP $< 5 + 0.01 * \Delta Z$ µm $\Delta Z > 500$ µm



IP of the tracks at the neutrino vertices

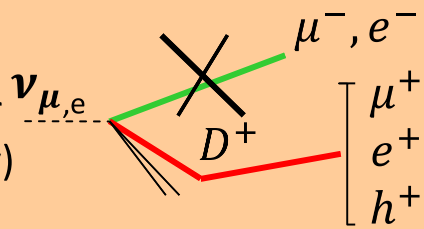


[Eur.Phys.J. C74 (2014) 2986]

$\nu_\mu \to \nu_\tau$ *background characterization*

In order of decreasing relevance

CC with charm production
(all channels)
If primary lepton is not identified and the daughter charge is not (or incorrectly) measured

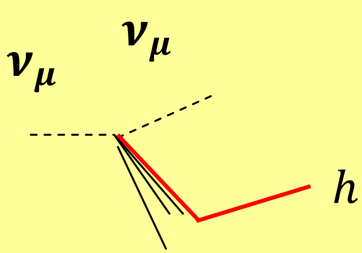


MC tuned on CHORUS data (cross section and fragmentation functions), validated with measured OPERA charm events.

Reduced by "track follow down", procedure and large angle scanning

[Eur.Phys.J. C74 (2014) 2986]

Hadronic interactions
Background for $\tau \to h$

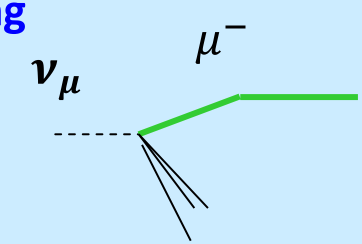


FLUKA + pion test beam data

Reduced by large angle scanning and nuclear fragment search

[PTEP9 (2014) 093C01]

Large angle muon scattering
Background for $\tau \to \mu$



Measurements in the literature (Lead form factor), simulations and dedicated test-beams

Reduced to negligible level

[arXiv:1506.08759]

Data sample

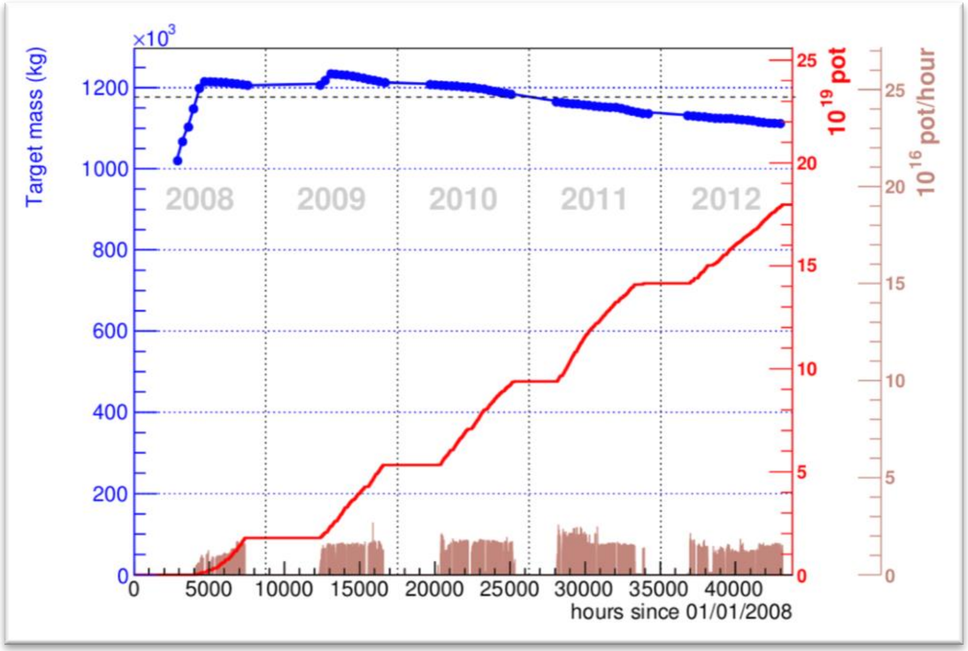
5 years CNGS run

$1.8 \cdot 10^{20}$ p.o.t. collected (80% of the design)

1.25 kton initial target mass (150 k bricks)

19505 neutrino interactions collected in the lead emulsion target

Year	Beam days	P.O.T. (10^{19})
2008	123	1.74
2009	155	3.53
2010	187	4.09
2011	243	4.75
2012	257	3.86
Total	**965**	**17.97**

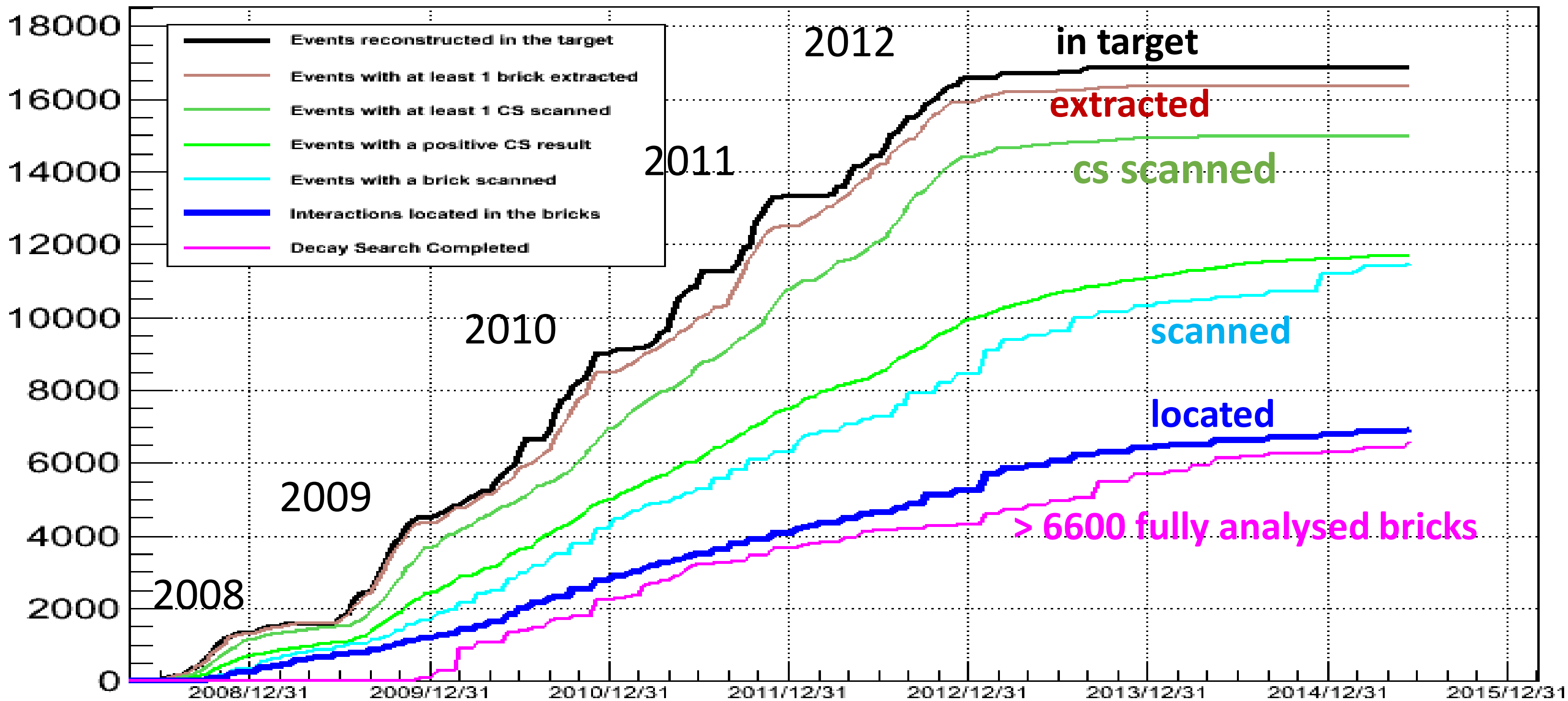


Data analysis

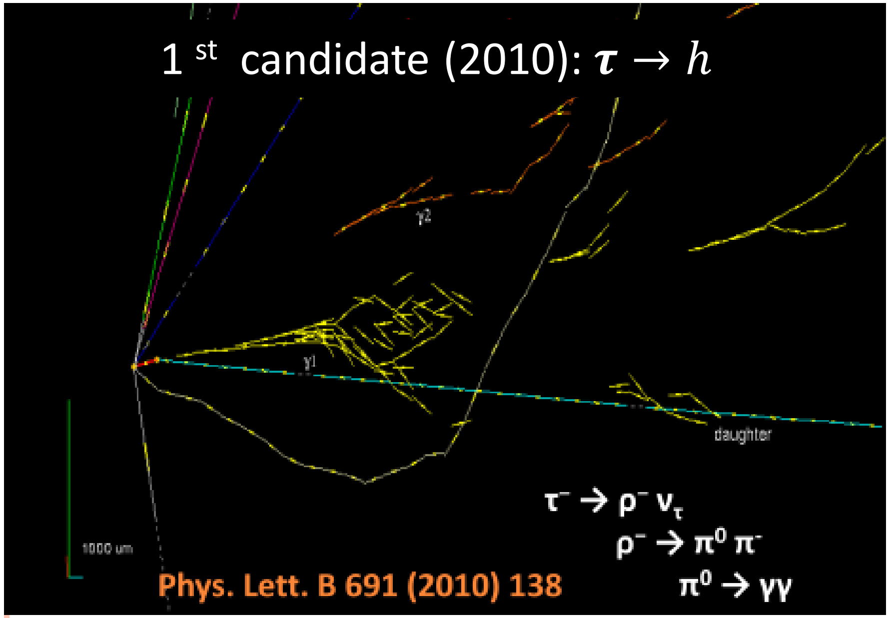
Bricks are ordered according to their probability of containing the interaction vertex

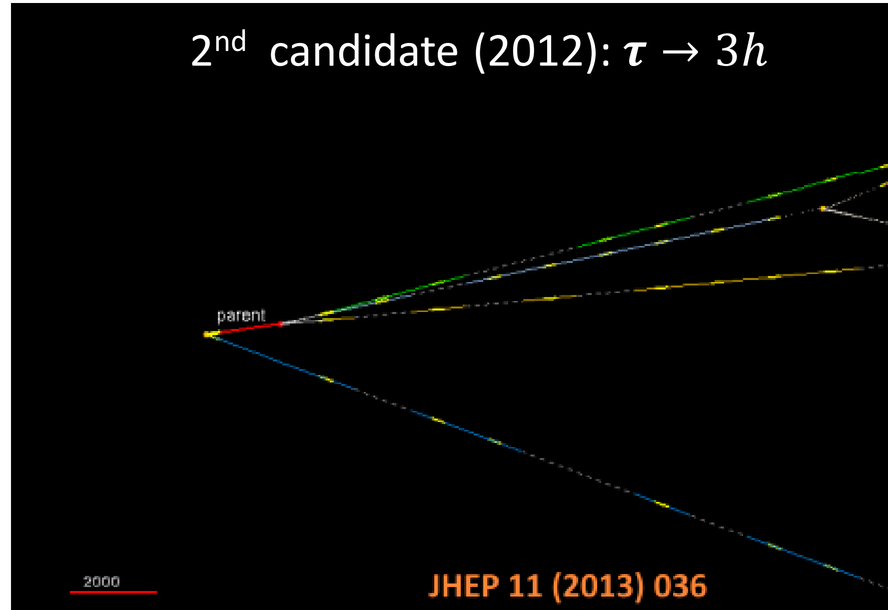
2008-09 completed up to the 4th brick

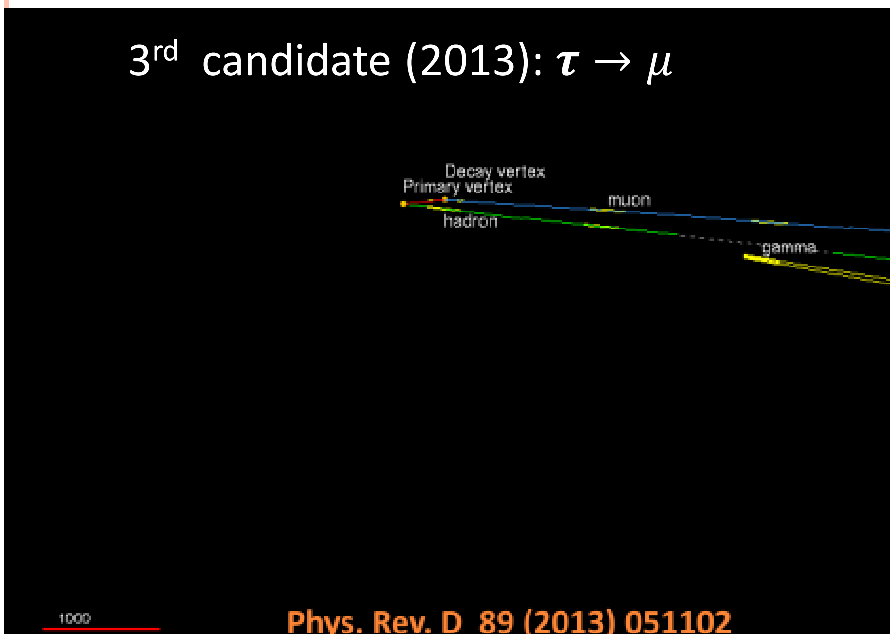
2010-12 completed up to the 2nd brick

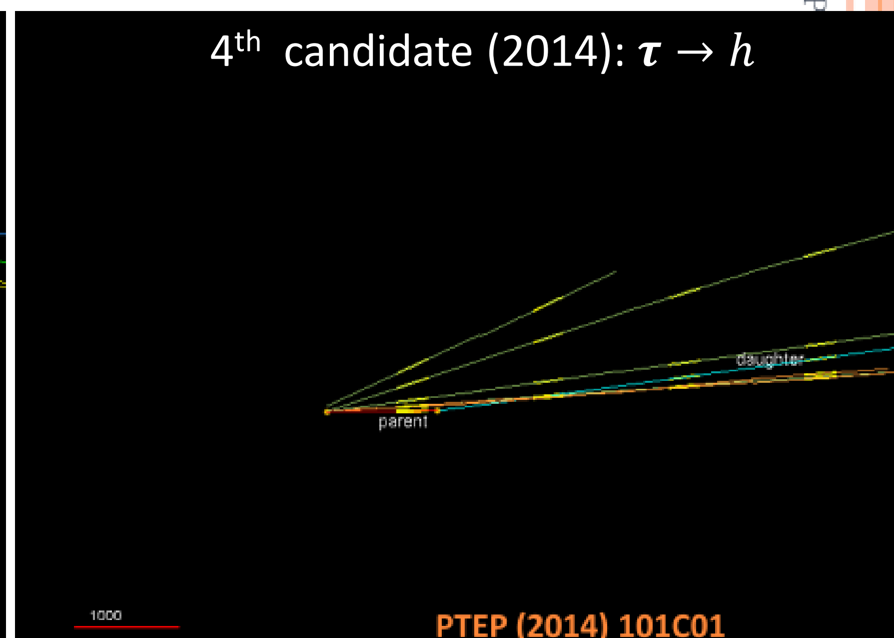


ν_τ gallery

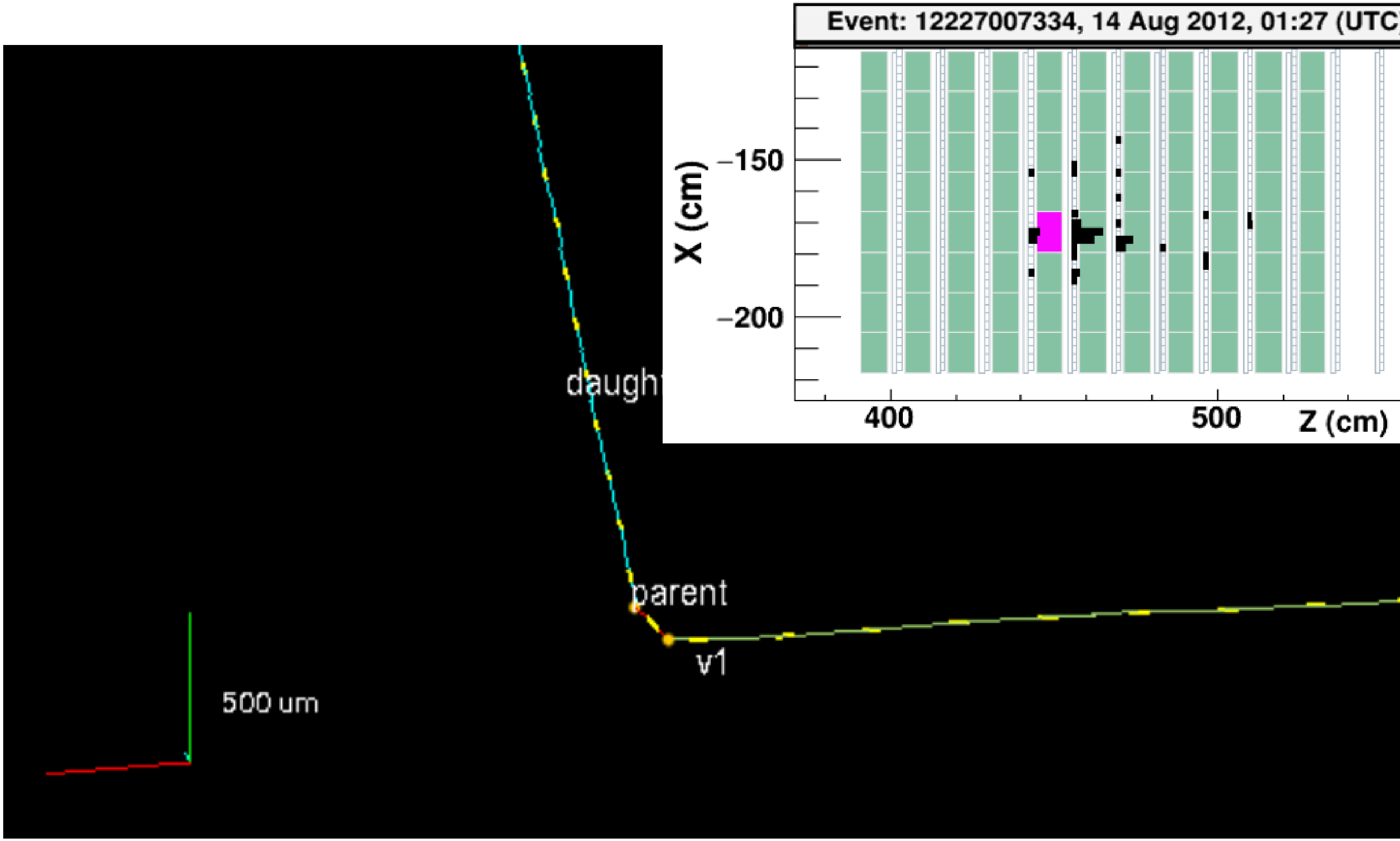








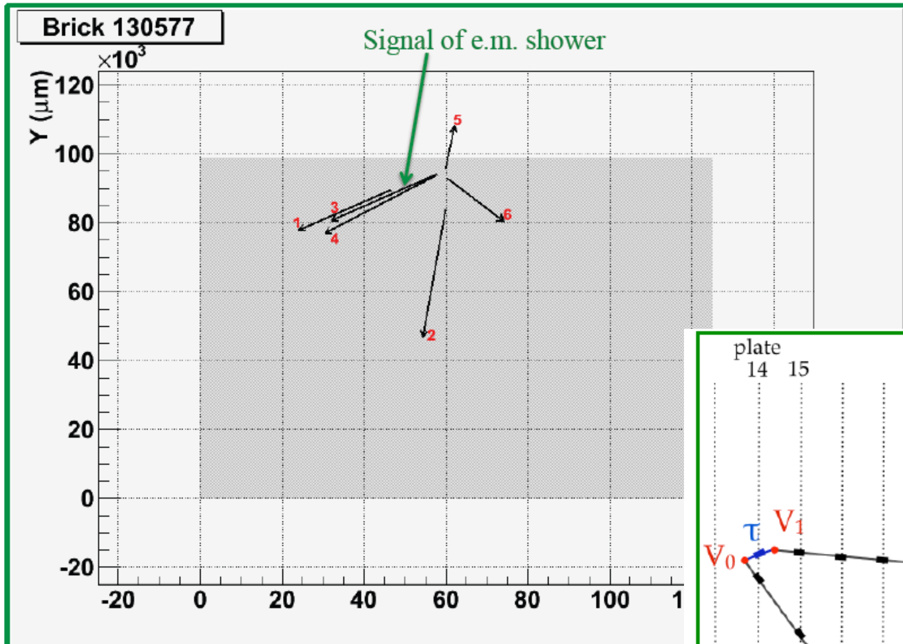
Fifth ν_t candidate



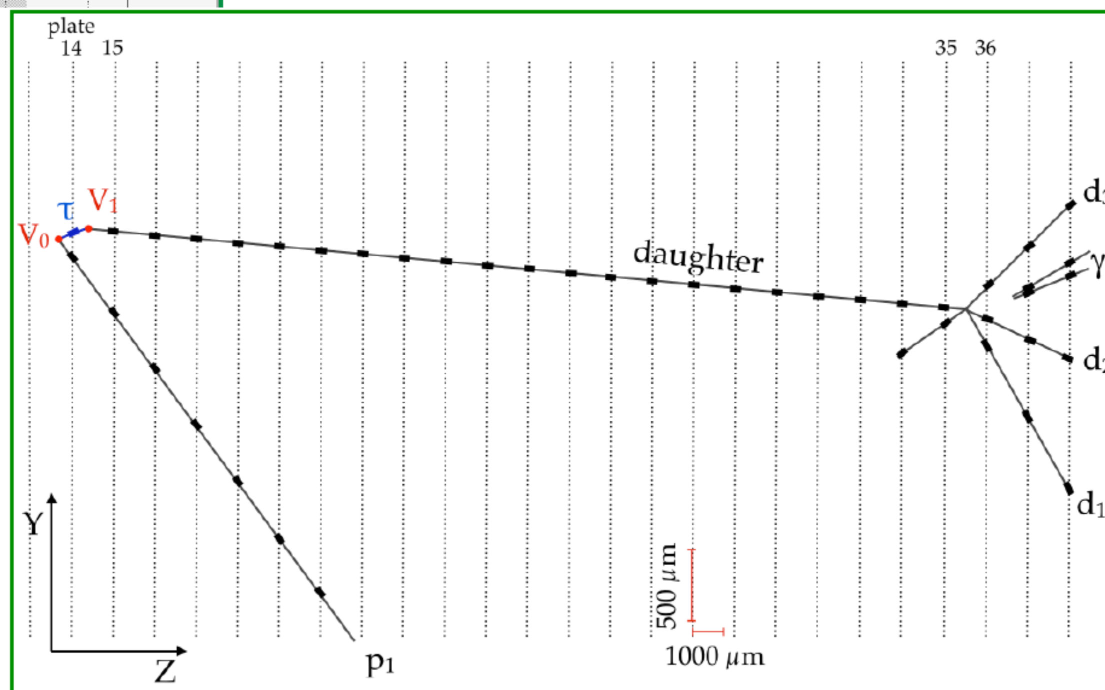
[arXiv:1507.01417] submitted to PRL

Fifth ν_τ candidate

CS films scanning results

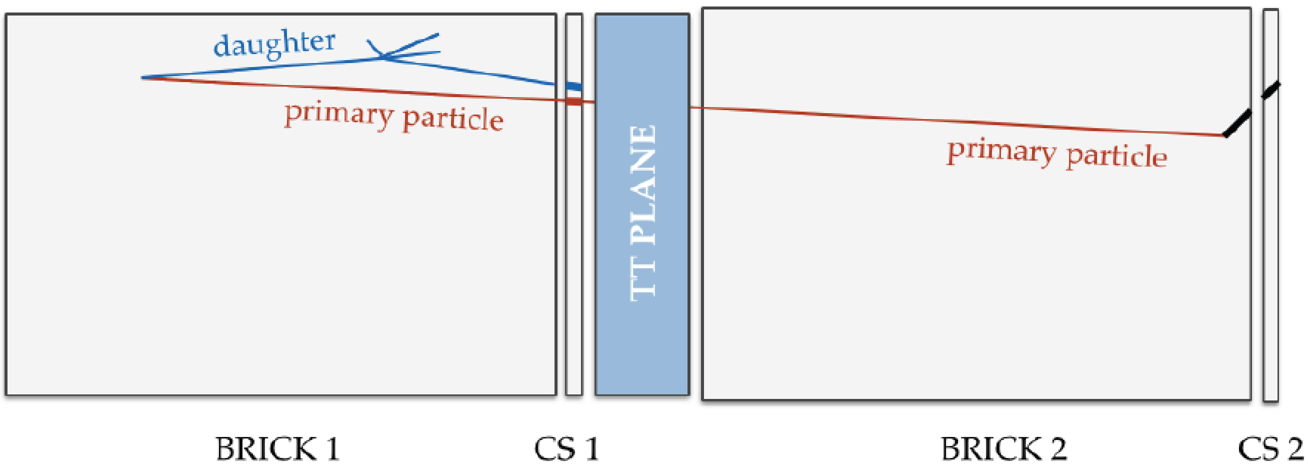


ECC scanning results



Fifth ν_τ candidate

PARTICLE IDENTIFICATION



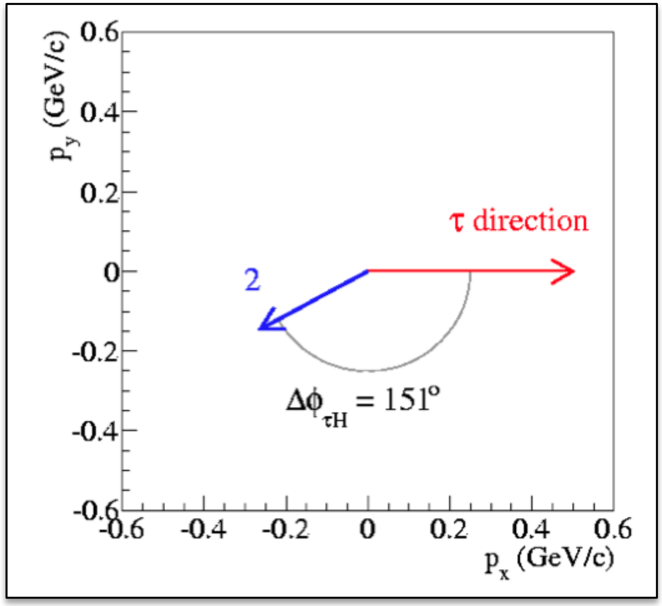
Primary particle
Followed in the downstream brick
Hadronic re-interaction: 1 visible particle

→ **Charm hypothesis discarded**

Daughter
Hadronic re-interaction in the first brick

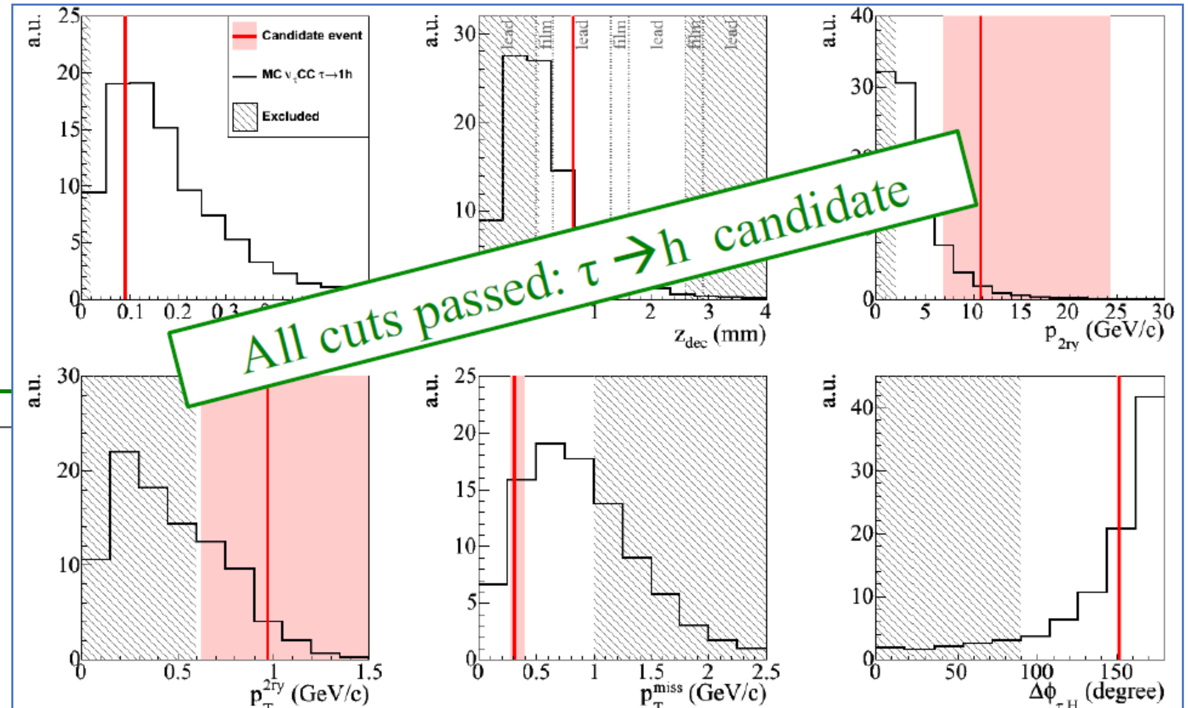
→ **Hadronic decay channel**

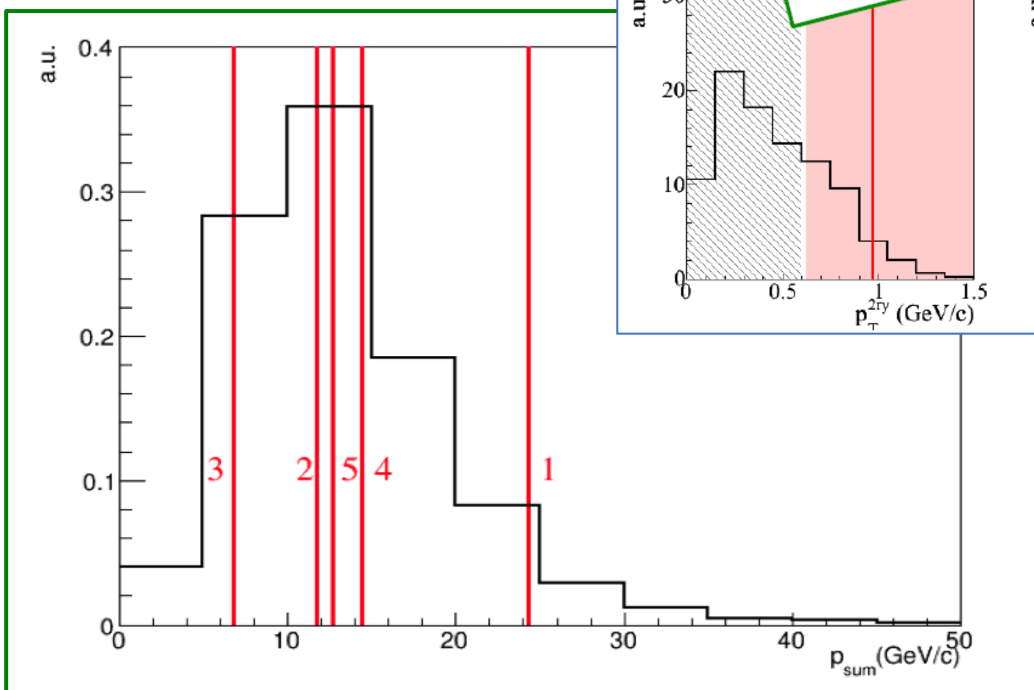
Fifth ν_τ candidate



Parameter	Measured value	Selection Criteria
$\Delta\phi_{\tau H}$ (^{o})	151±1	>90
p_T^{miss} (GeV/c)	0.3 ± 0.1	<1
θ_{kink} (mrad)	90 ± 2	>20
z_{dec} (μm)	634 ± 30	[44, 2600]
p^{2ry} (GeV/c)	11^{+14}_{-4}	>2
p_T^{2ry} (GeV/c)	$1.0^{+1.2}_{-0.4}$	>0.6 (no γ attached)

Fifth ν_τ candidate





Sum of the visible tracks' momenta

ν_τ analysis results

Observed Data: 4 hadronic + 1 muonic candidates

Channel	Expected background	Expected signal	Observed
$\tau \to 1h$	0.04 ± 0.01	0.52 ± 0.10	3
$\tau \to 3h$	0.17 ± 0.03	0.73 ± 0.14	1
$\tau \to \mu$	0.004 ± 0.001	0.61 ± 0.12	1
$\tau \to e$	0.03 ± 0.01	0.78 ± 0.16	0
Total	0.25 ± 0.05	2.64 ± 0.53	5

P-value $=1.1 \cdot 10^{-7}$

Exclusion of background-only hypothesis: 5.1 σ

Measurement of Δm^2_{23}

$$N_{\nu_\tau} \propto \int \phi(E)\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)\epsilon(E)\sigma(E)dE$$
$$\propto (\Delta m^2_{32})^2 L^2 \int \phi(E)\epsilon(E)\frac{\sigma(E)}{E^2}dE$$

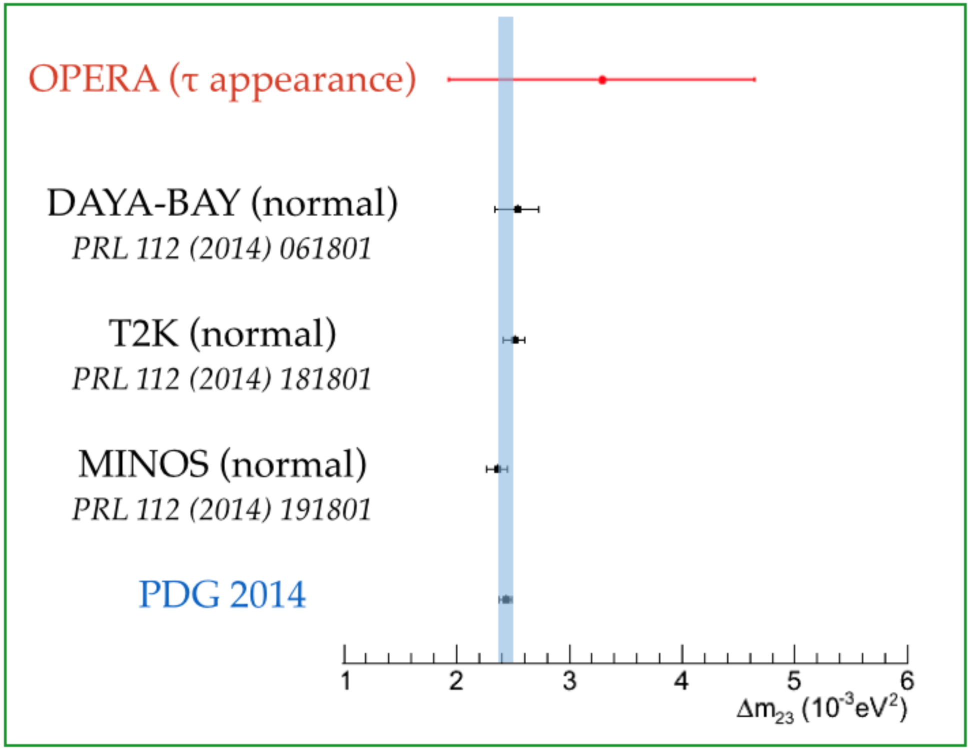
$\left({}^{L}/_{\langle E\rangle}\right)_{opera}$ ~43 km/GeV

$\left({}^{L}/_{\langle E\rangle}\right)_{PEAK}$ ~500 km/GeV

$\mathbf{\Delta m^2_{23}}$ dependence

90% C.L. intervals
by Feldman & Cousins method

$$\mathbf{\Delta m^2_{23} = [2.0 - 4.7]\, 10^{-3}\ eV^2}$$
(assuming full mixing)



Sterile neutrinos

Appearance probability be modified by one extra (sterile) state (3+1 scheme)

~ standard oscillation

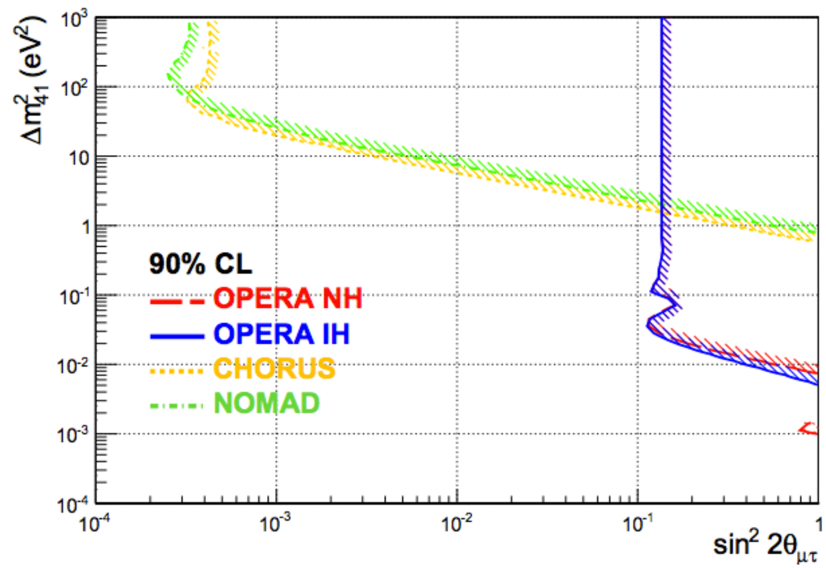
pure exotic oscillation

$$P_{\nu_\mu \to \nu_\tau} = 4|U_{\mu 3}|^2|U_{\tau 3}|^2 \sin^2\frac{\Delta_{31}}{2} + 4|U_{\mu 4}|^2|U_{\tau 4}|^2 \sin^2\frac{\Delta_{41}}{2}$$

interference terms

$$\begin{aligned}
&+ 2\Re[U^*_{\mu 4}U_{\tau 4}U_{\mu 3}U^*_{\tau 3}] \sin\Delta_{31} \sin\Delta_{41} \\
&- 4\Im[U^*_{\mu 4}U_{\tau 4}U_{\mu 3}U^*_{\tau 3}] \sin^2\frac{\Delta_{31}}{2} \sin\Delta_{41} \\
&+ 8\Re[U^*_{\mu 4}U_{\tau 4}U_{\mu 3}U^*_{\tau 3}] \sin^2\frac{\Delta_{31}}{2} \sin^2\frac{\Delta_{41}}{2} \\
&+ 4\Im[U^*_{\mu 4}U_{\tau 4}U_{\mu 3}U^*_{\tau 3}] \sin\Delta_{31} \sin^2\frac{\Delta_{41}}{2}
\end{aligned}$$

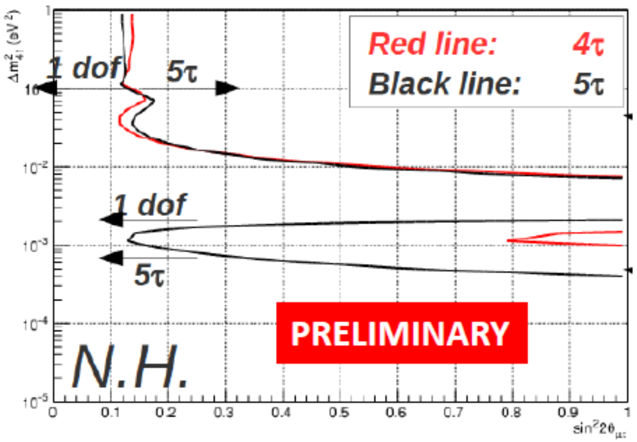
$\nu_\mu \to \nu_\tau$

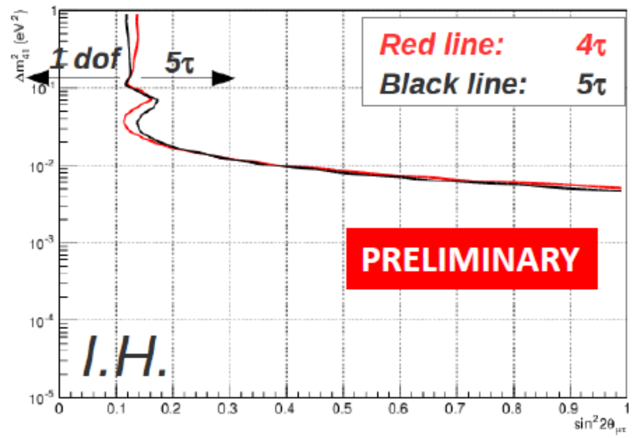


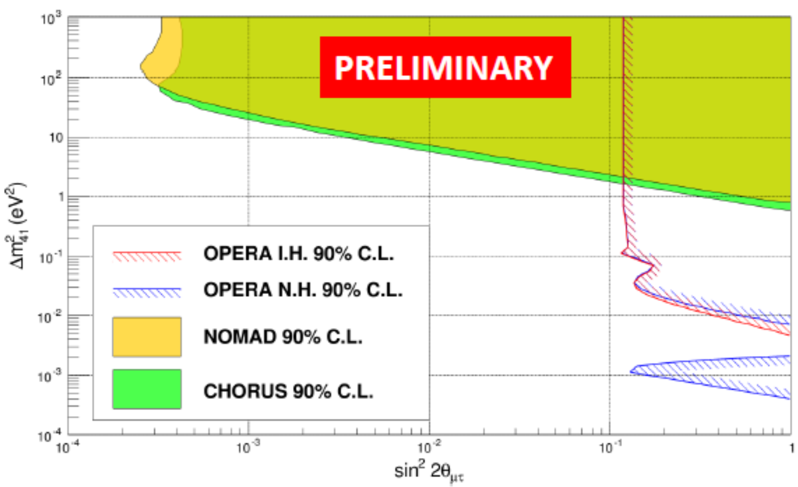
[JHEP 074 (2015) 0315]

First limits on $|U_{\mu 4}|^2|U_{\tau 4}|^2$ from direct measurement of $\boldsymbol{\nu_\tau}$

Preliminary OPERA updated results (5 ν_τ events)



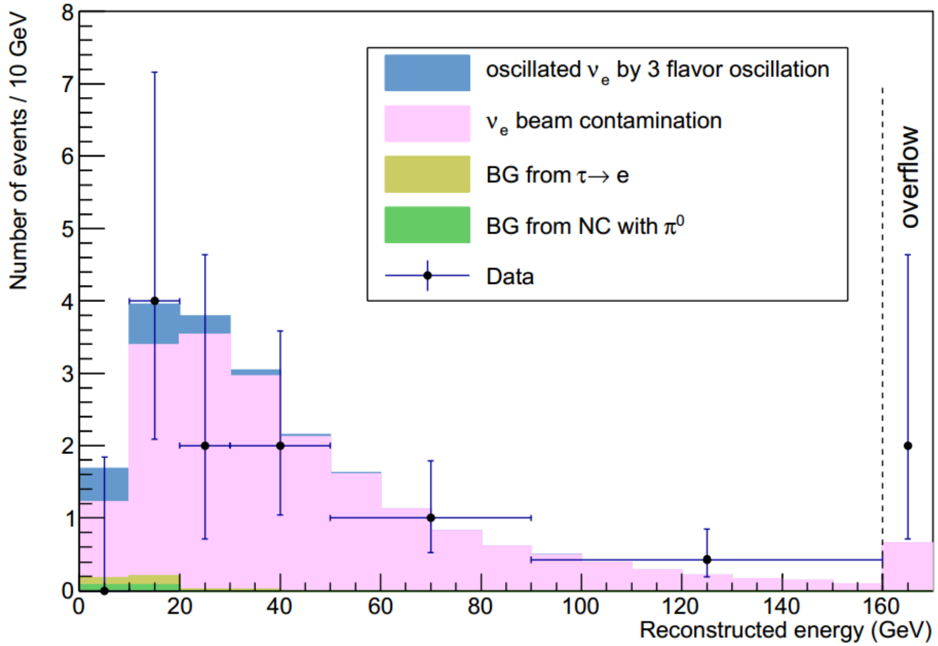




Full analysis with GLOBES (matter effects, Δm^2_{21} included, profiled out on Δm^2_{31})

Old result from 2008+2009 data sample (30% of total)

$\nu_\mu \rightarrow \nu_e$



JHEP 4, 1307 (2013)

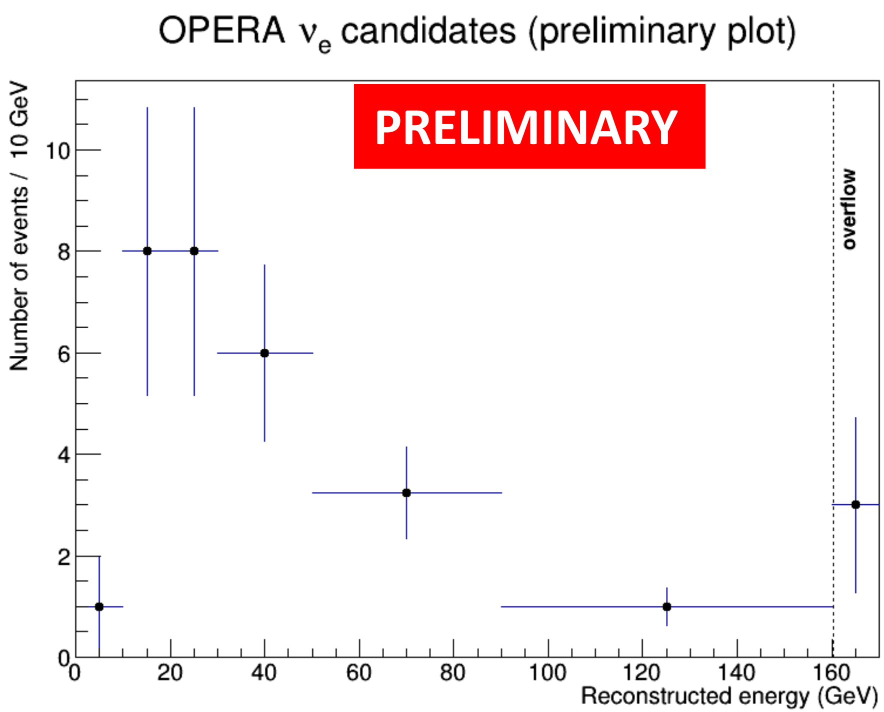
		E<20 GeV
ν_e candidates	19	4
background	19.8±2.8	4.6

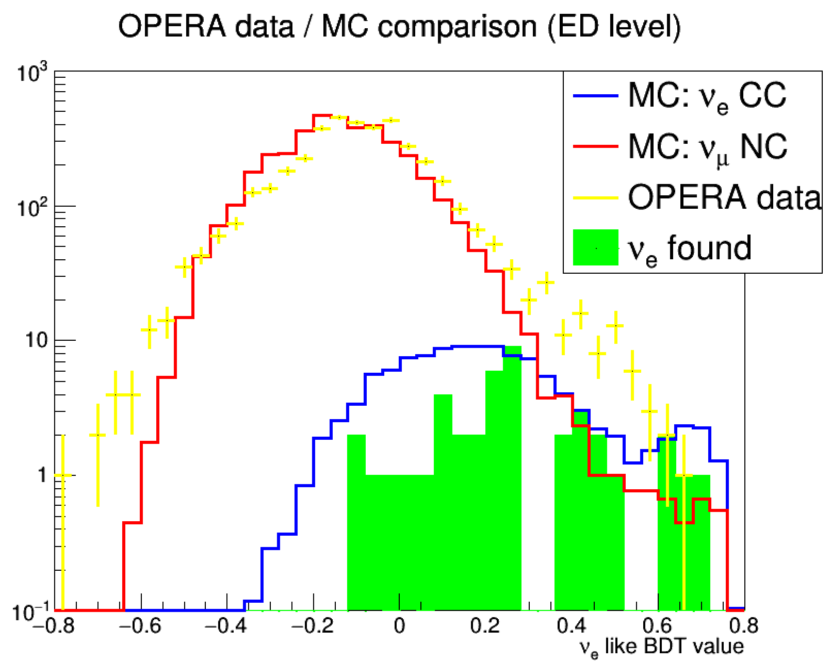
Compatible with expectation from intrinsic ν_e component in the CNGS ν_μ beam: 0.9%

We may put rough limits to exclude mixing on θ_{14} with a 2 flavour model

**** Very approximate analysis, see e.g. A.Palazzo, PRD 91, 91301(R) (2015)**

NEW study on-going : ν_e candidates selection by emulsion analysis on the full data sample





		E<20 GeV
ν_e candidates (30% data)	19	4
ν_e candidates (all data)	52	9

PRELIMINARY

Good confirmation of ν_e events from Electronic Detectors (via Boost-Decision-Tree)

Conclusions

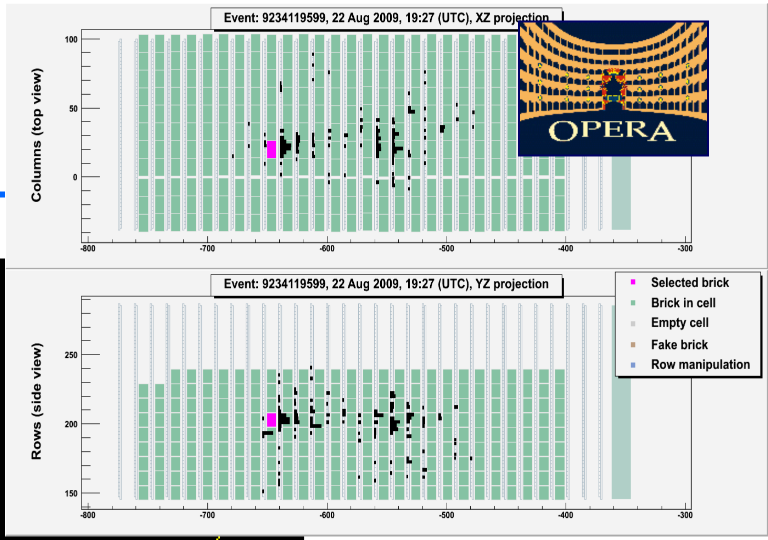
- 1.8 x 10^{20} pot by CNGS from 2008-12 (80% of design).
- Analysis of an extended data sample. Improved background evaluation
- **5 $\boldsymbol{\nu_\tau}$ candidates** so far with a 0.25 event background
- No oscillation hypothesis excluded at **5.1 σ.**

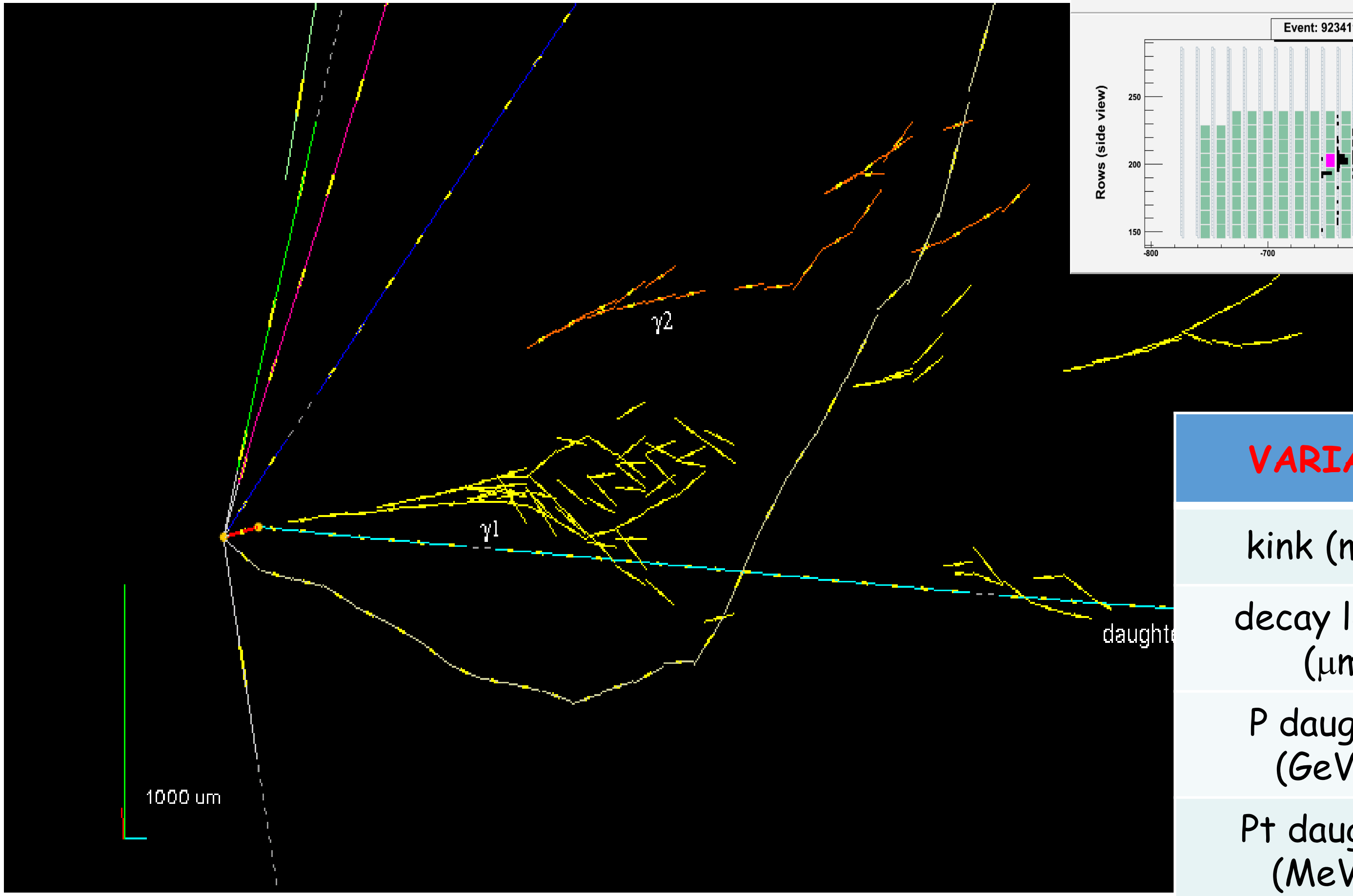
  → **discovery of $\boldsymbol{\nu_\tau}$ appearance in the CNGS beam**
- Search for anomalies in $\boldsymbol{\nu_\mu} \rightarrow \boldsymbol{\nu_e}$ and $\boldsymbol{\nu_\mu} \rightarrow \boldsymbol{\nu_\tau}$ at a peculiar L/E.

  First limits on $|U_{\mu 4}|^2 |U_{\tau 4}|^2$ from direct measurement of $\boldsymbol{\nu_\tau}$.

BACKUP
- BACKGROUND

First ν_τ candidate



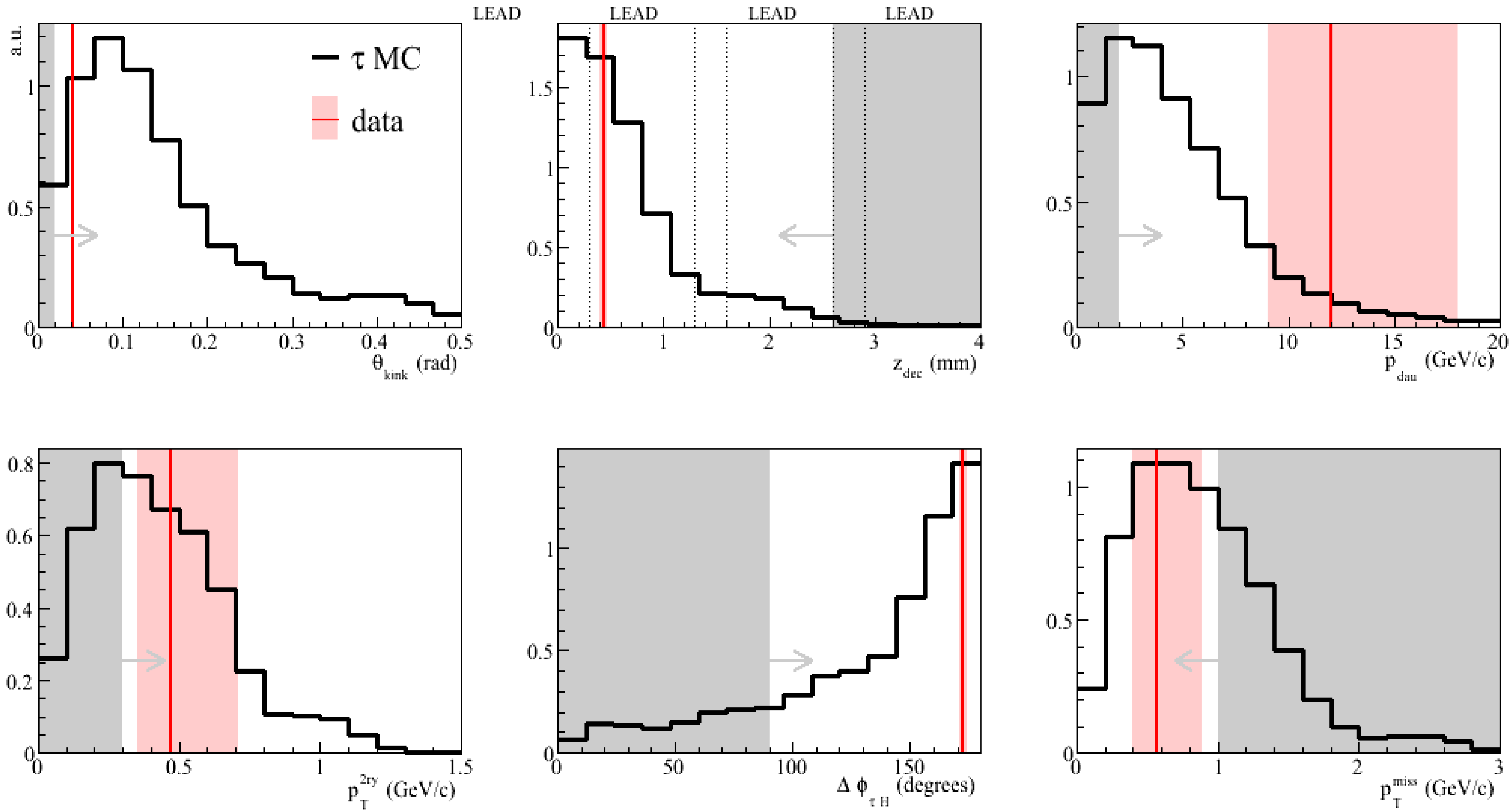


VARIABLE	AVERAGE
kink (mrad)	41 ± 2
decay length (μm)	1335 ± 35
P daughter (GeV/c)	12^{+6}_{-3}
Pt daughter (MeV/c)	470^{+230}_{-120}
missing Pt (MeV/c)	570^{+320}_{-170}
ϕ (deg)	173 ± 2

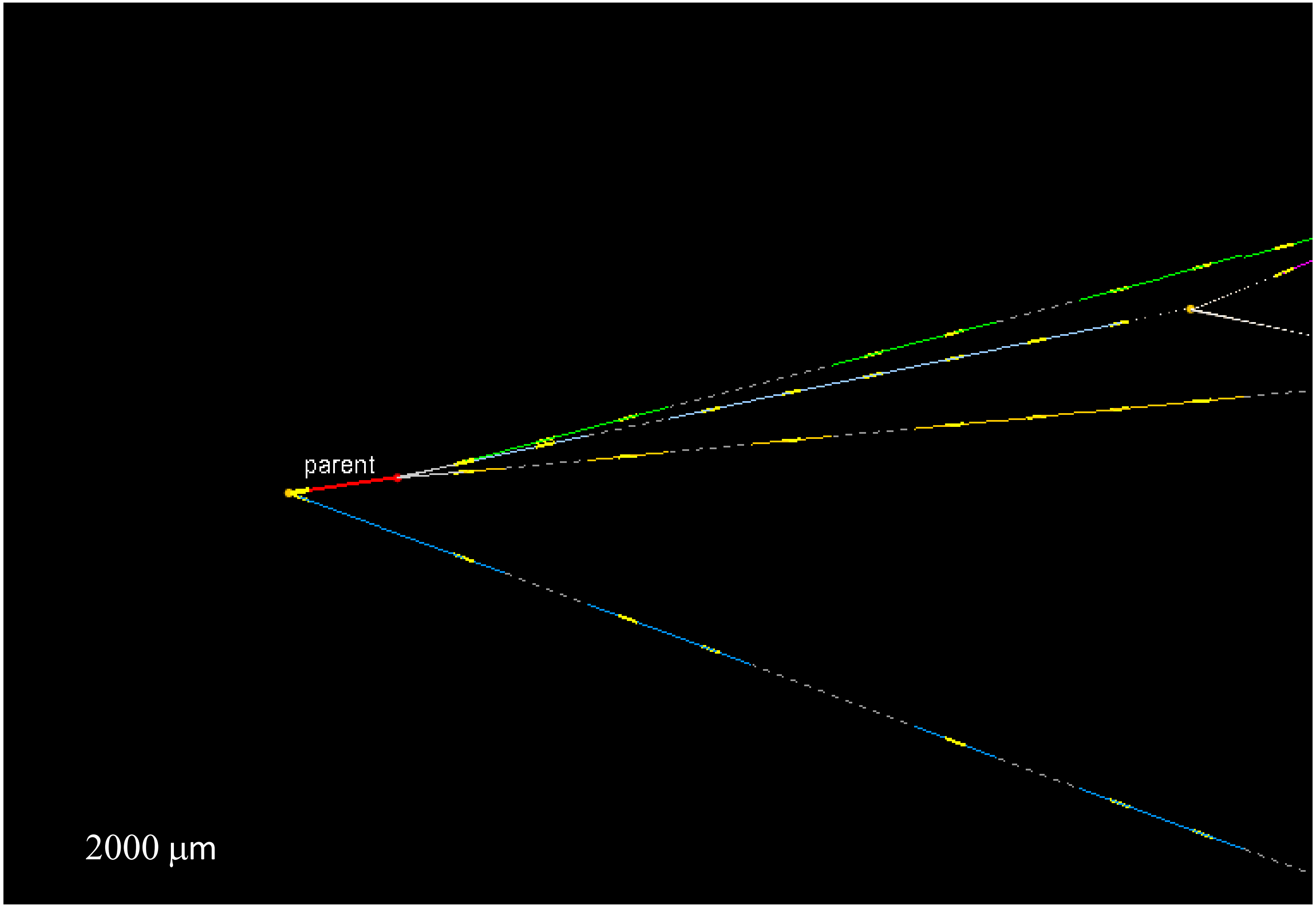
$\tau \rightarrow \rho\ (\pi^- \pi^0)\ \nu_\tau$

Ref :***Phys.Lett.B691:138-145 (2010)***

Kinematical cuts for a candidate event

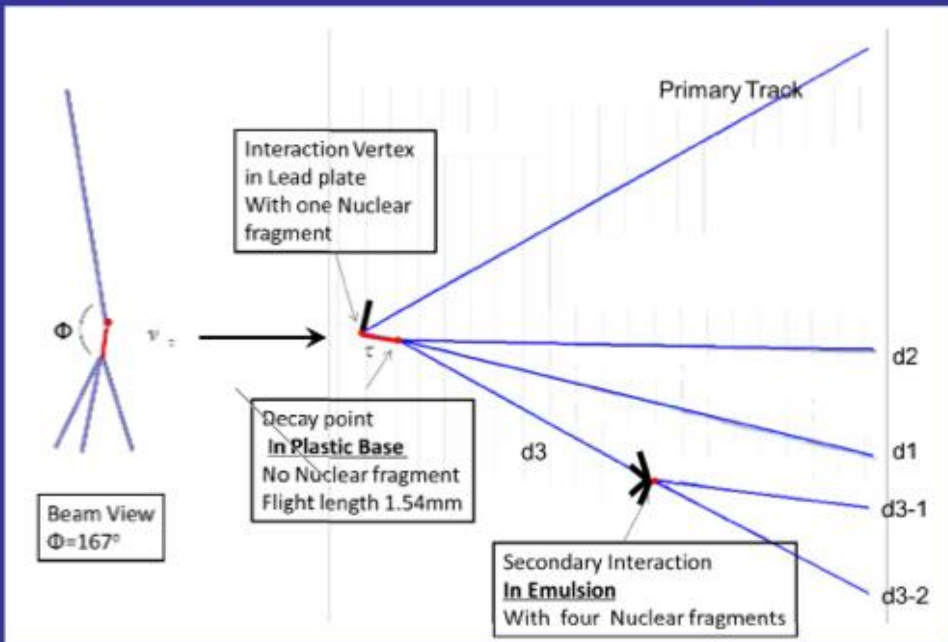


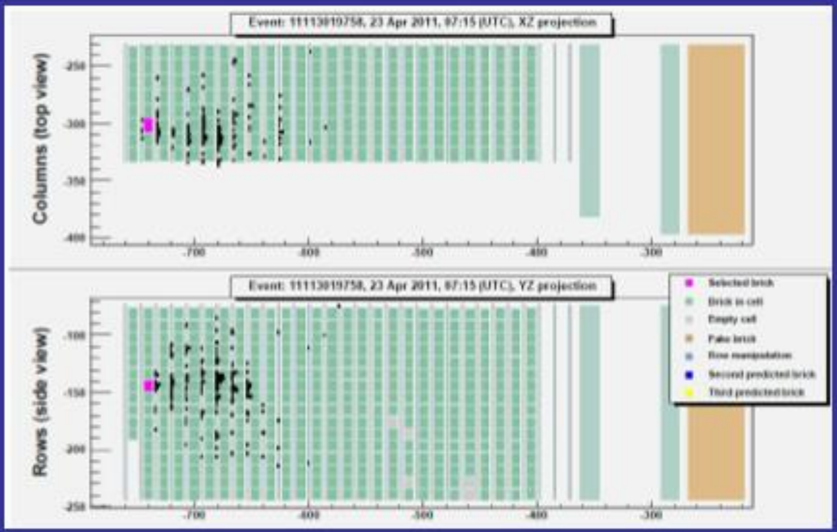
Second ν_τ candidate



$\nu_\mu \to \nu_\tau$ oscillation search

Ref: JHEP 11 (2013) 036





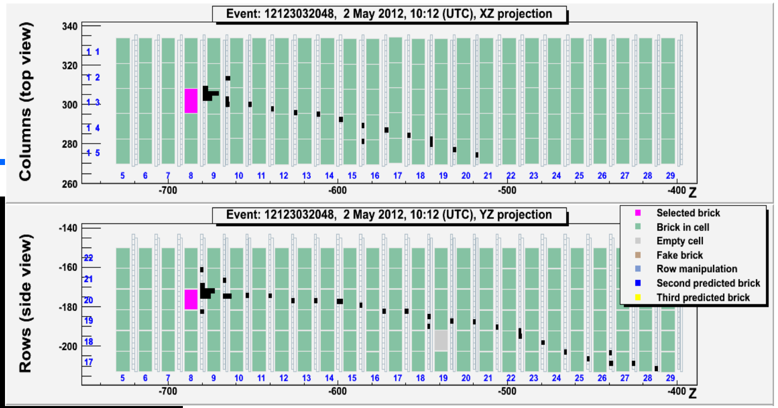
No muon detected at the primary vertex:

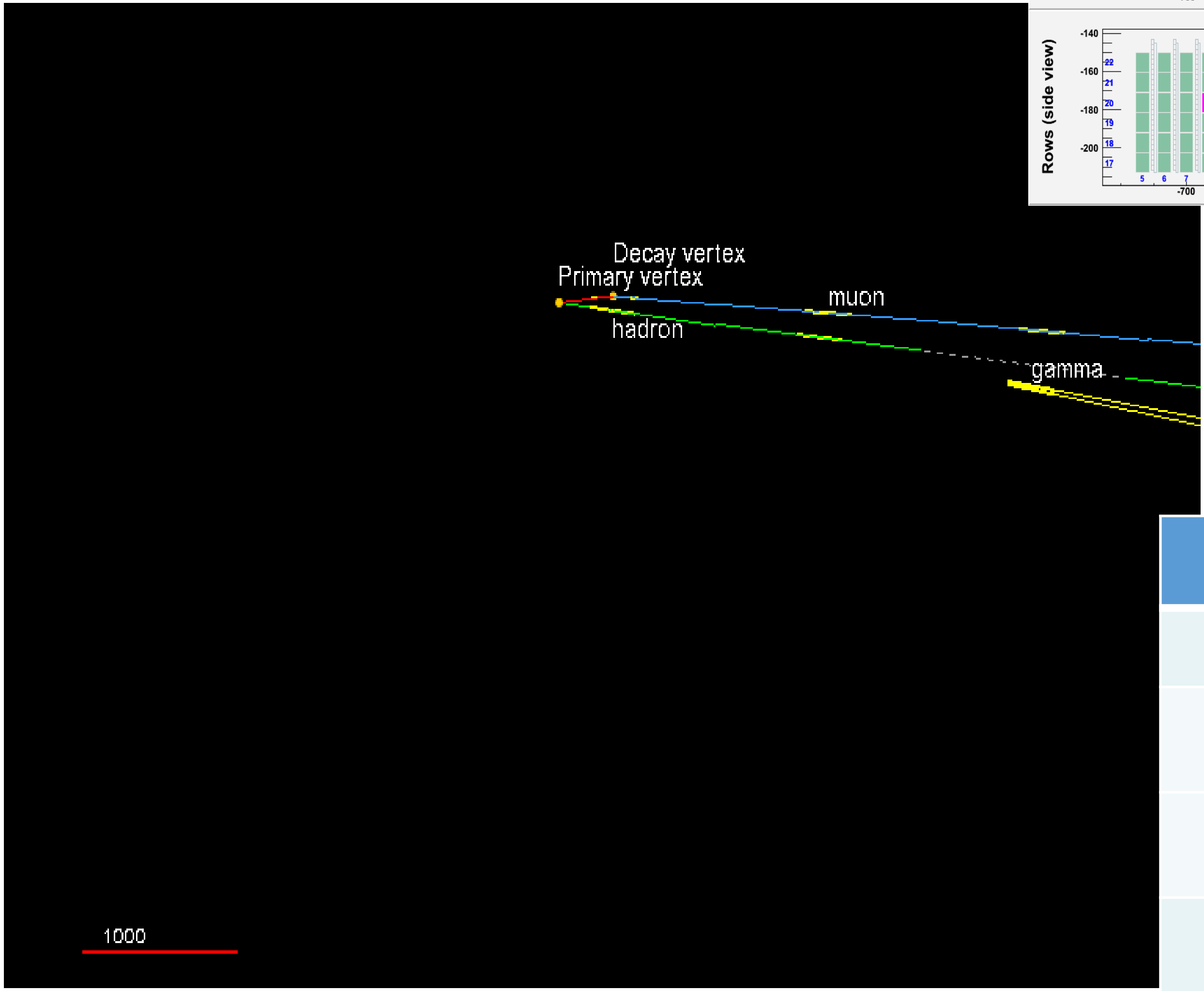
track other than τ lepton candidate not compatible with muon hypothesis based on momentum – range correlation

Event kinematics

	Cut	Value	Error
Phi (Tau - Hadron) [degree]	>90	167.8	± 1.1
average kink angle [mrad]	< 500	87.4	± 1.5
Total momentum at 2ry vtx [GeV/c]	> 3.0	8.4	± 1.7
Min Invariant mass [GeV/c²]	0.5 < < 2.0	0.96	± 0.13
Invariant mass [GeV/c²]	0.5 < < 2.0	0.80	± 0.12
Transverse Momentum at 1ry vtx [GeV/c]	< 1.0	0.31	± 0.11

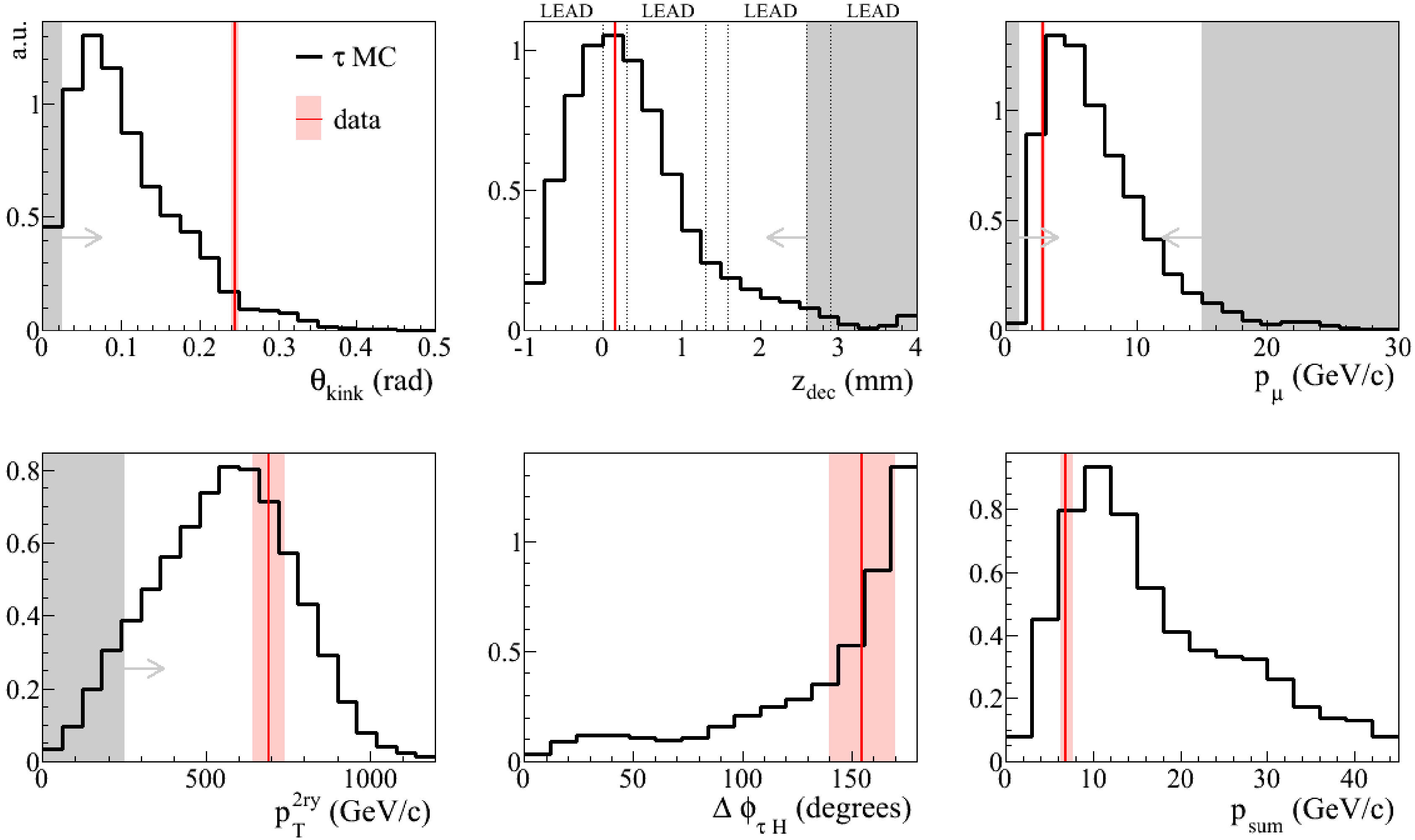
Third ν_τ candidate



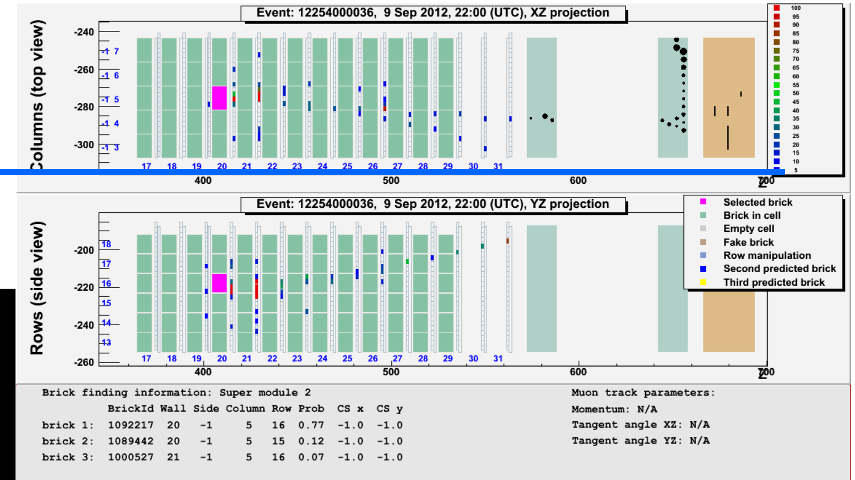


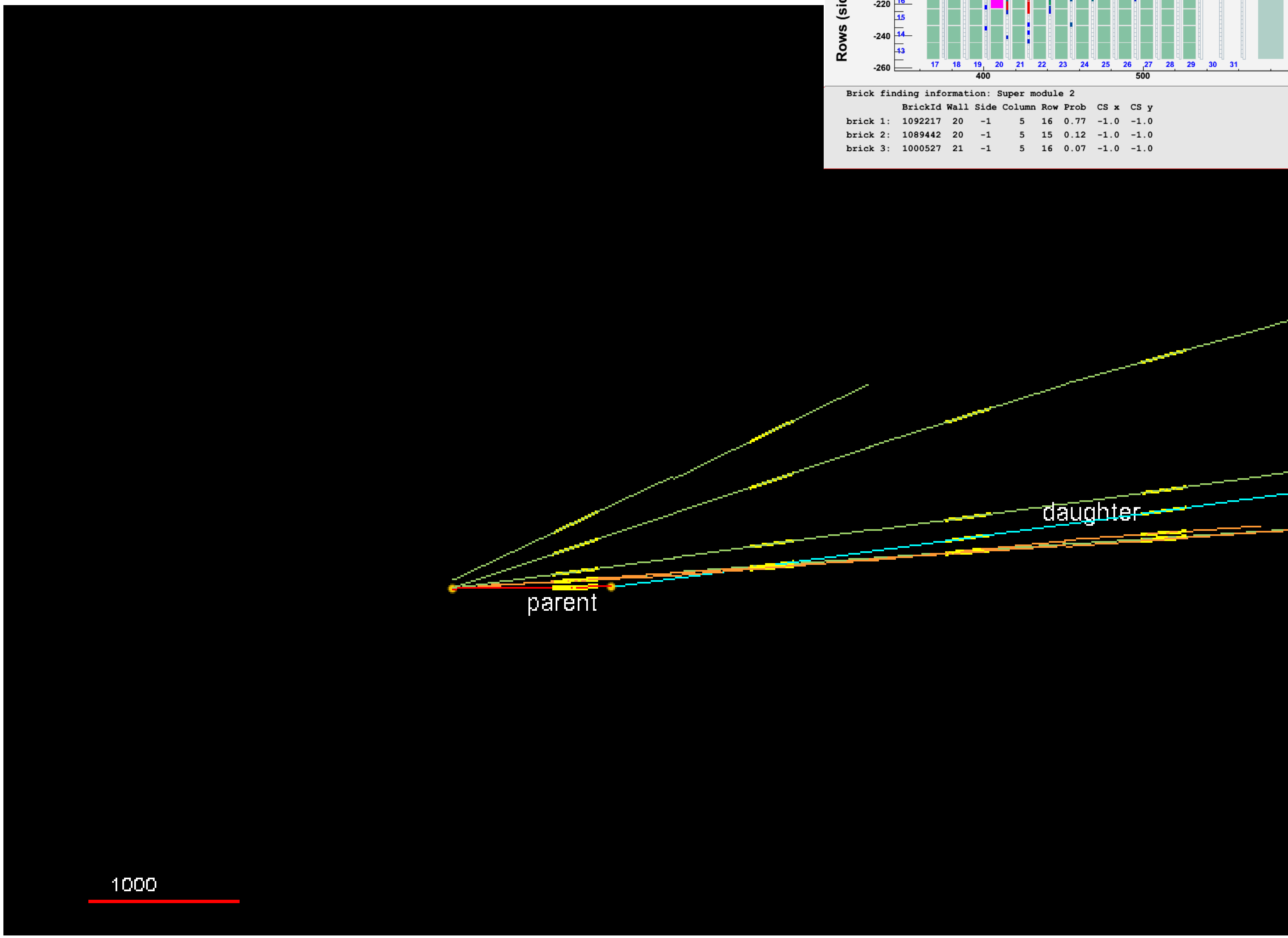
VARIABLE	AVERAGE
kink (mrad)	245 ± 5
decay length (μm)	376 ± 10
P daughter (GeV/c)	2.8 ± 0.2
Pt daughter (MeV/c)	690 ±50
ϕ (deg)	154.5 ± 1.5

PHYSICAL REVIEW D 89 (2014) 051102(R)

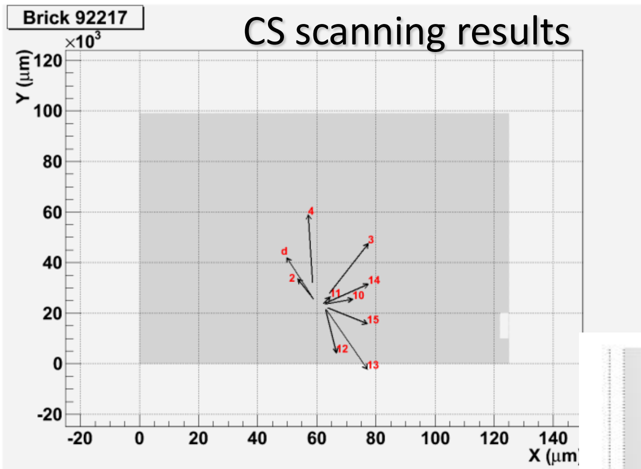

a.u.
τ MC
data
θkink (rad)
LEAD
LEAD
LEAD
LEAD
zdec (mm)
pμ (GeV/c)
pT2ry (GeV/c)
Δ φτH (degrees)
psum (GeV/c)

fourth ν_τ candidate

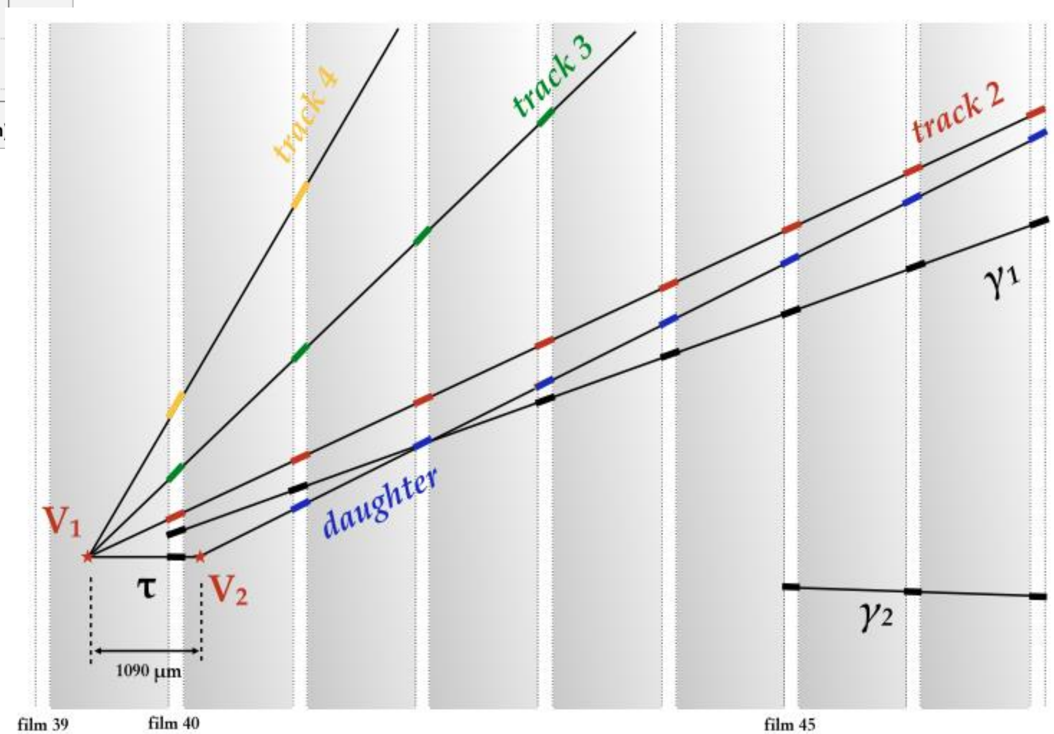




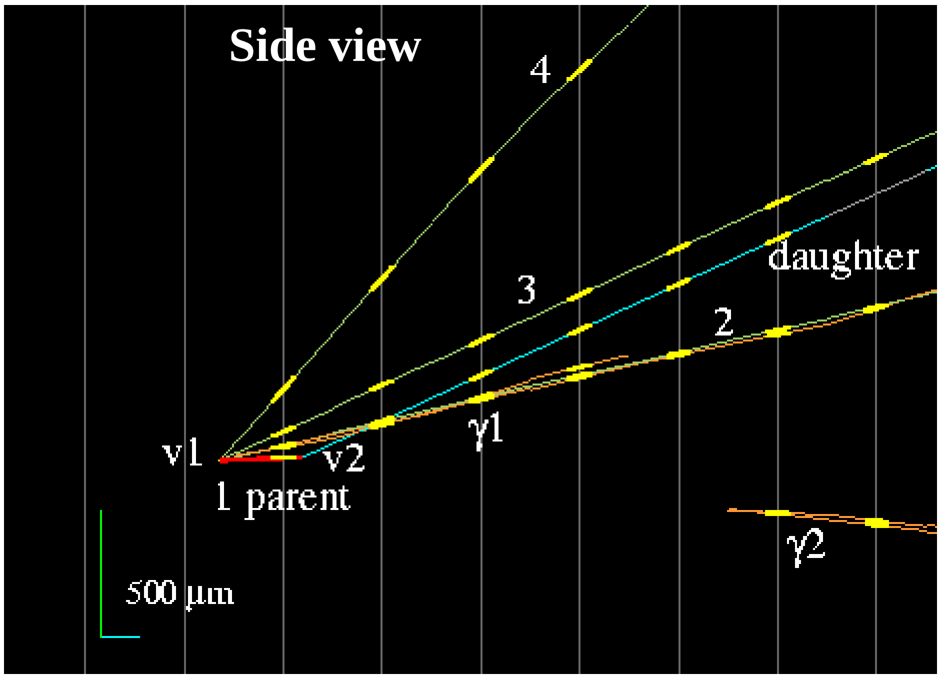
fourth ν_τ candidate

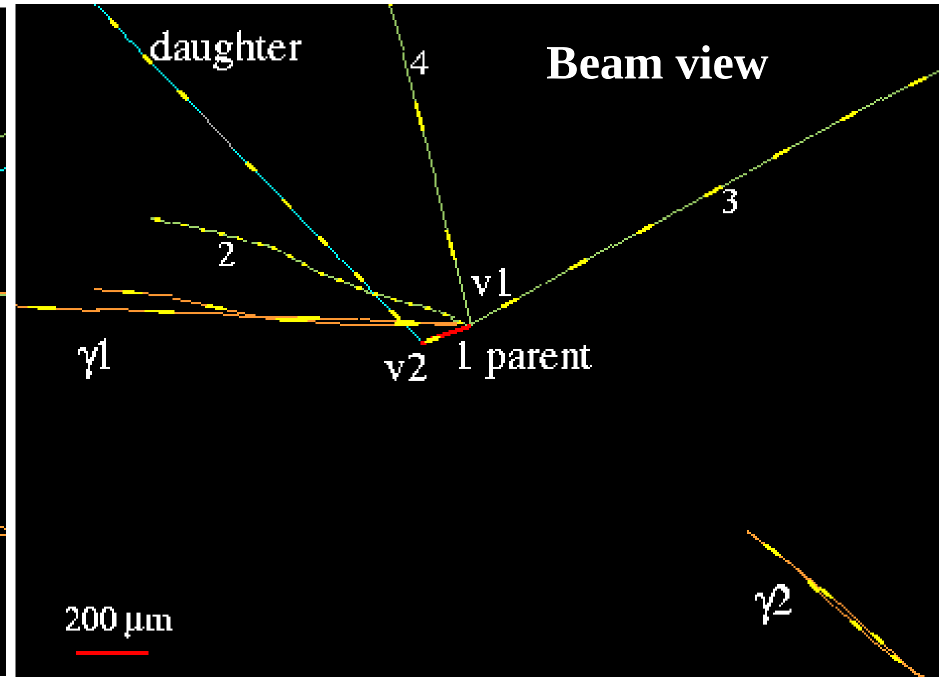


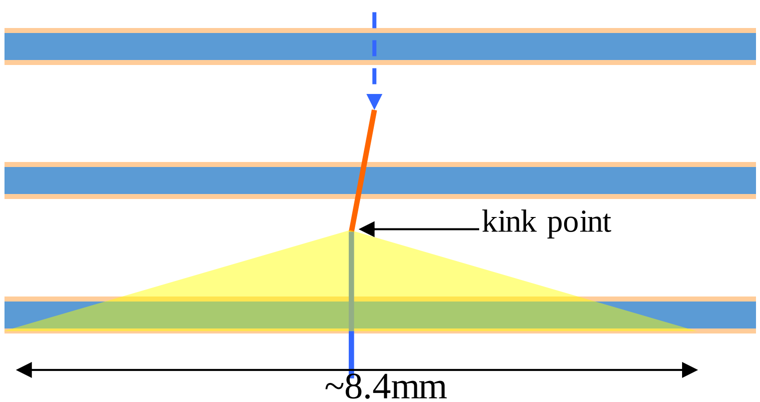
ECC scanning results



fourth ν_τ candidate



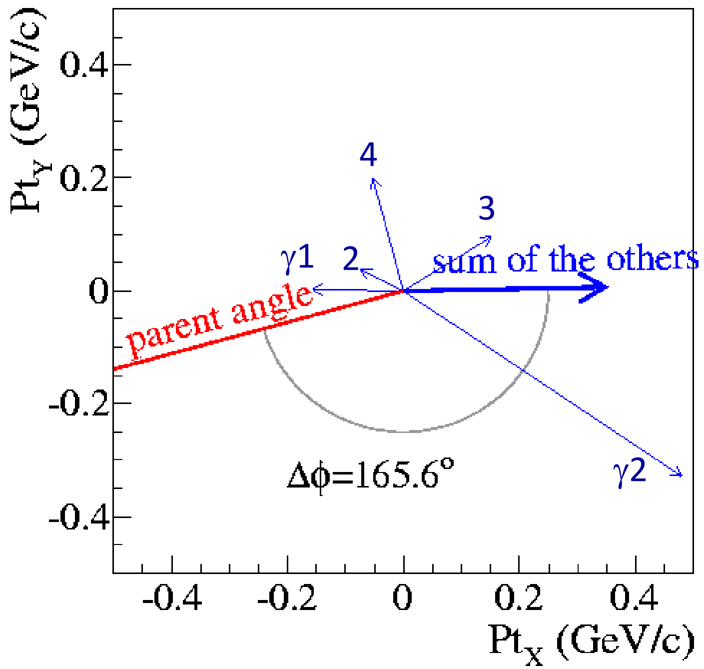




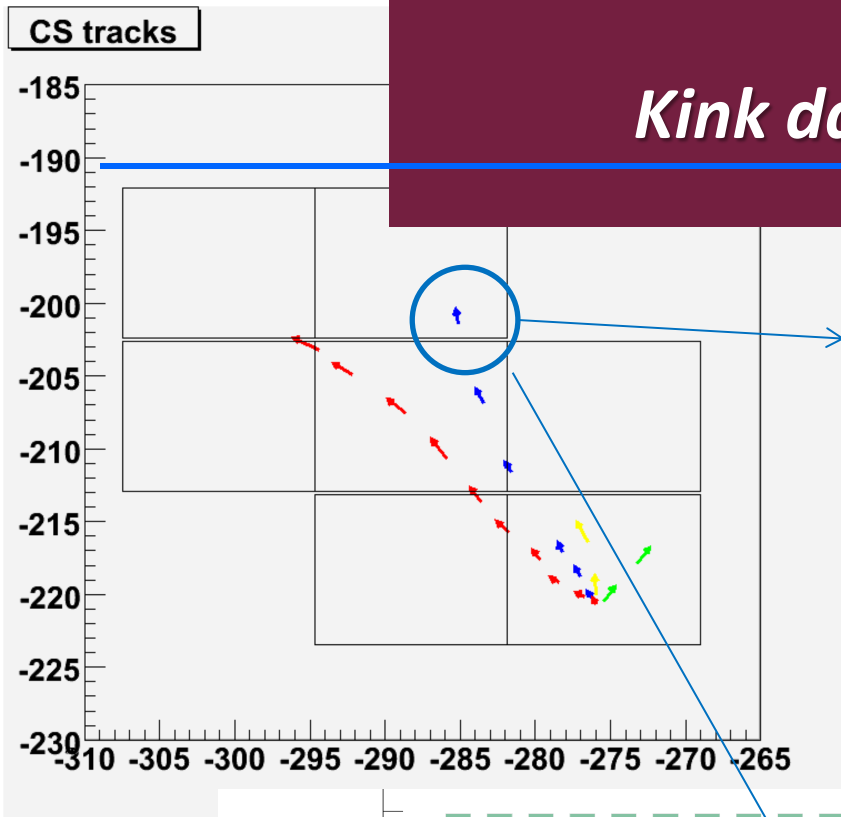
Search for nuclear fragments
in an extended angular range $|\tan\theta| \leq 3.5$
No track found

fourth ν_τ candidate

	Values	Selection
P daughter (GeV/c)	$6.0^{+2.2}_{-1.2}$	> 2
Kink P_t (GeV/c)	$0.82^{+0.30}_{-0.16}$	> 0.6
P_t at 1ry (GeV/c)	$0.55^{+0.30}_{-0.20}$	< 1.0
Phi (degrees)	166^{+2}_{-31}	> 90
Kink angle (mrad)	137 ± 4	> 20
Decay position (μm)	1090 ± 30	< 2600



Kink daughter track follow down

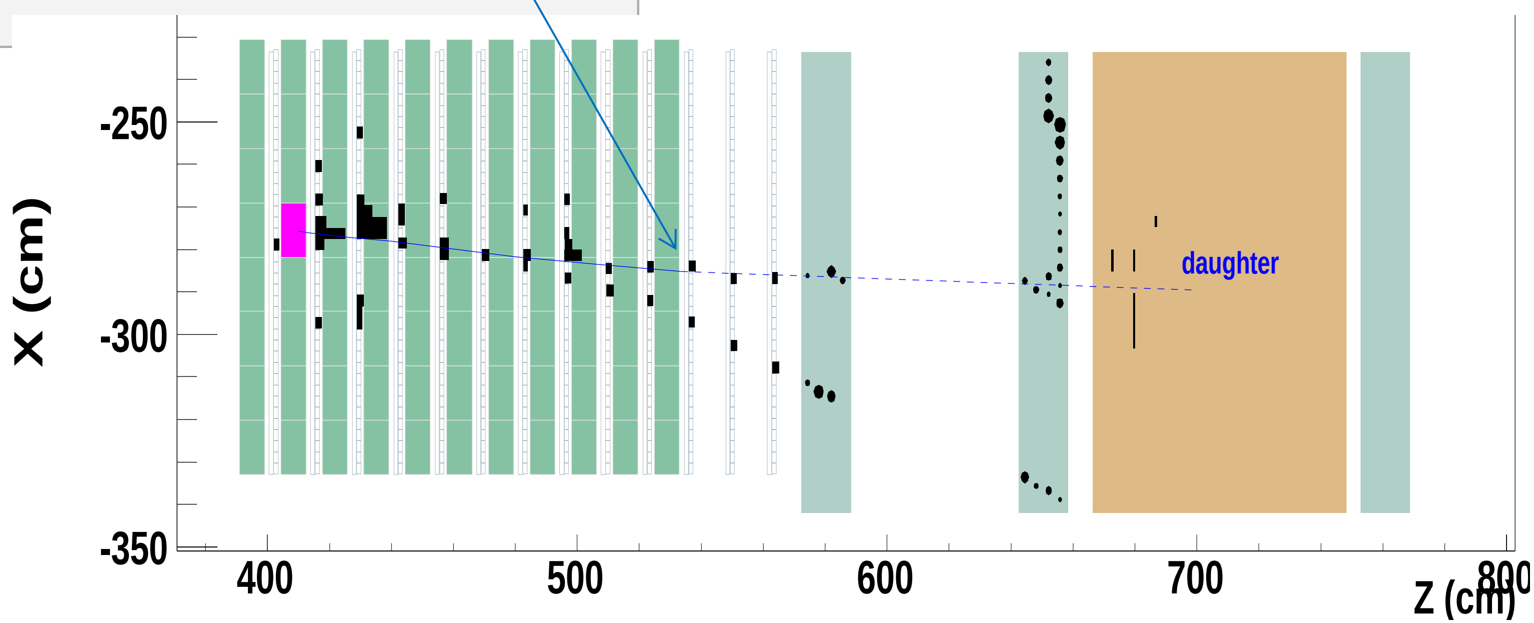


Found in the CS of the most downstream brick

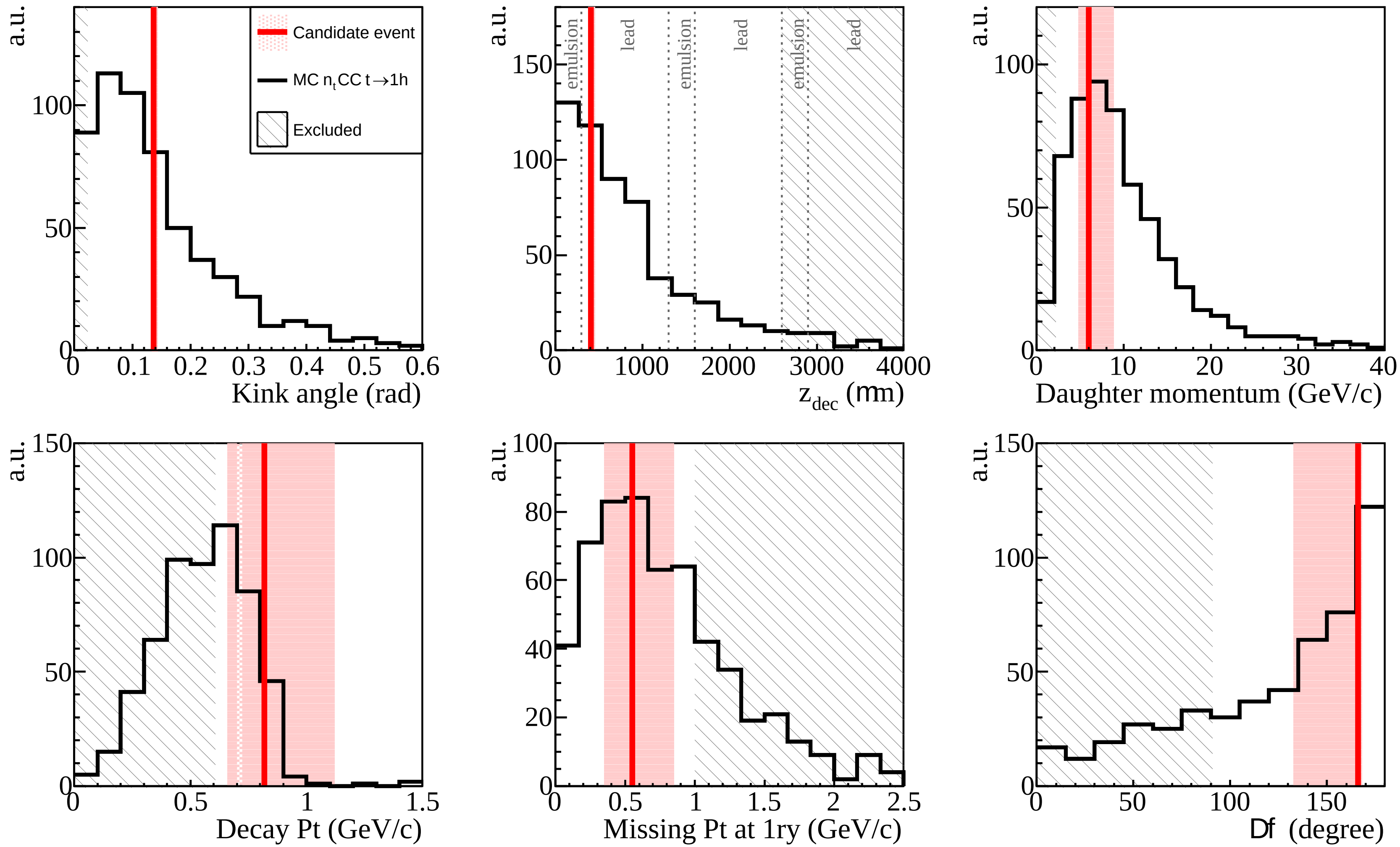
P = $6.0^{+2.0}_{-1.2}$ GeV/c

Range/momentum → hadron

$$D = \frac{L}{R_{lead}(p)} \frac{\rho_{average}}{\rho_{lead}} = 0.15$$



Fourth ν_τ candidate

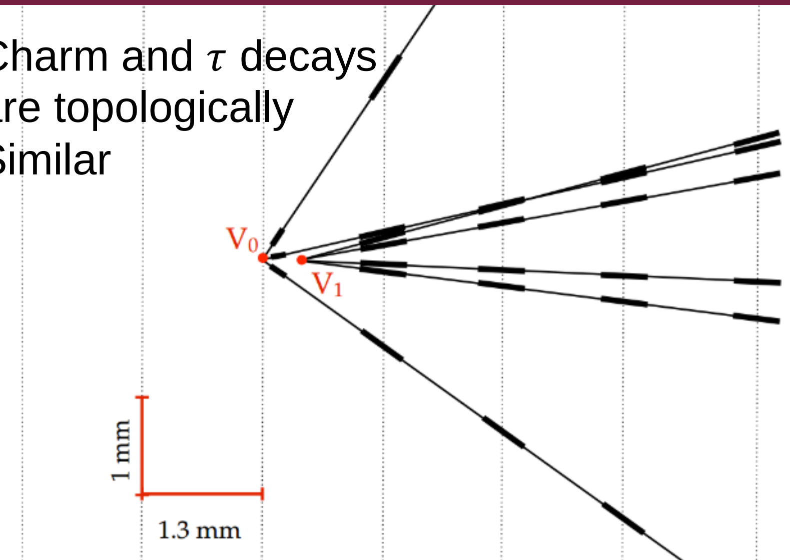


Validation with the CNGS charm events sample

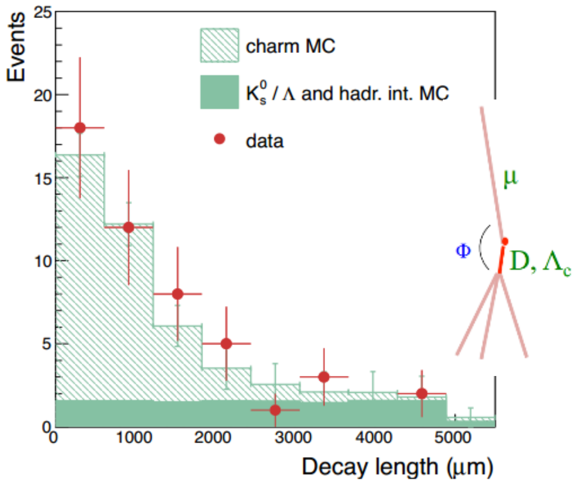
Test for: reconstruction efficiencies, description of kinematical variables, charm background.

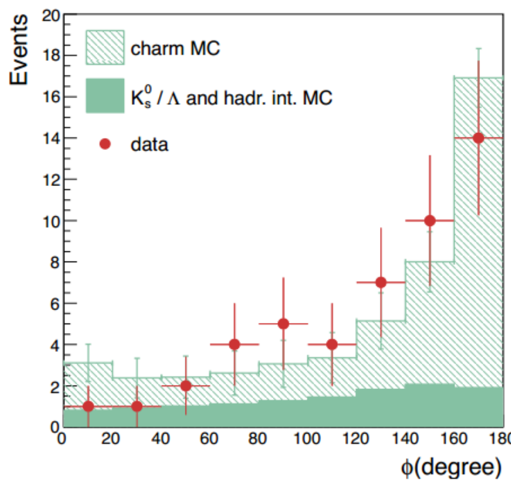
54 ± 4 expected ↔ 50 observed

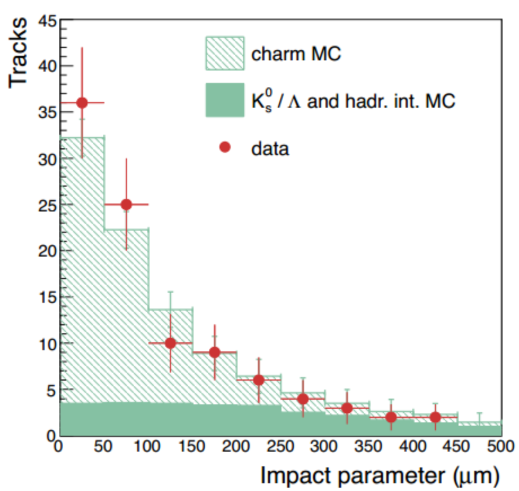
Charm and τ decays are topologically Similar

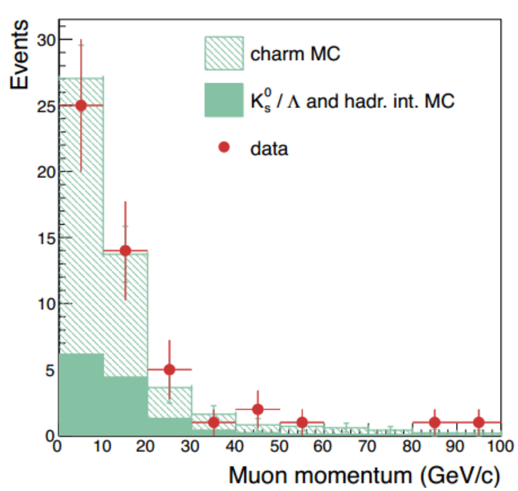


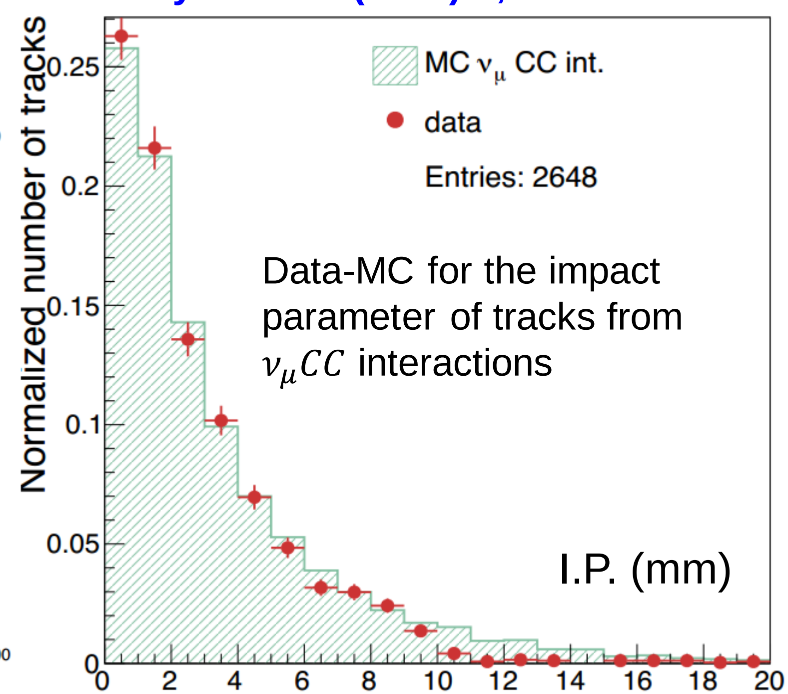
Eur.Phys.J. C74 (2014) 8, 2986









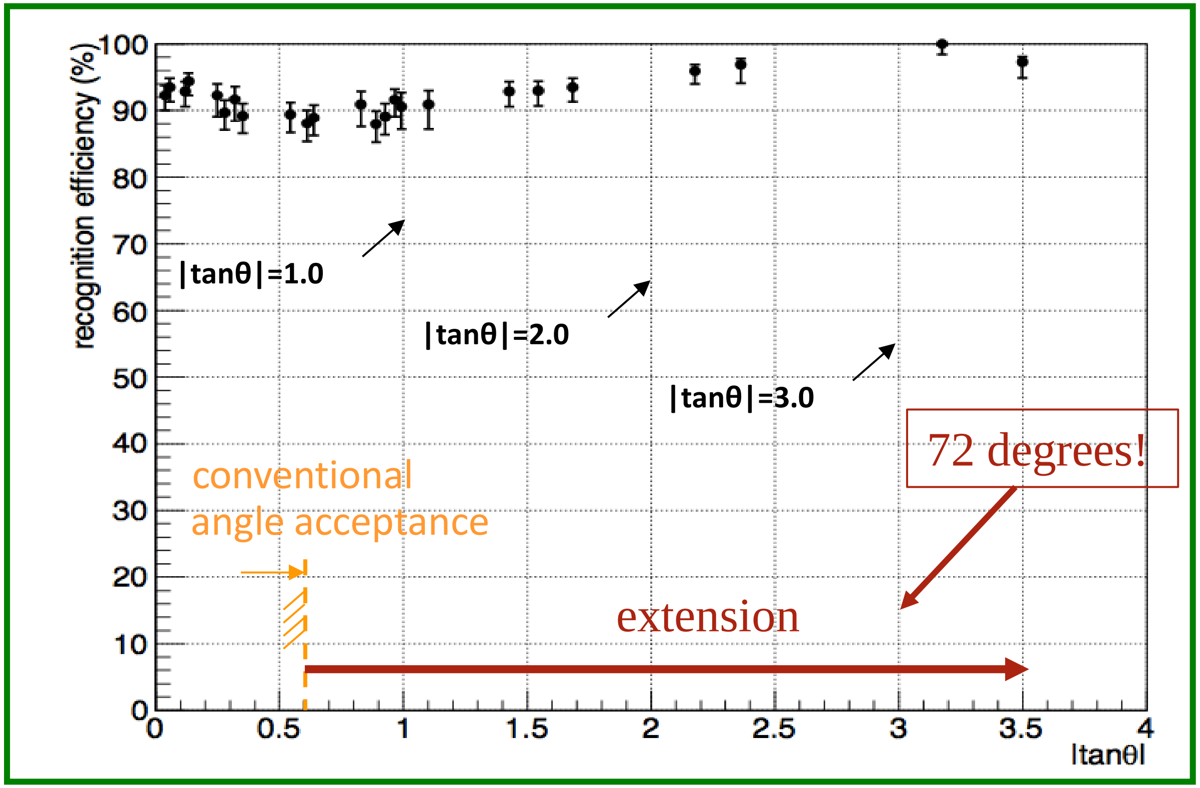


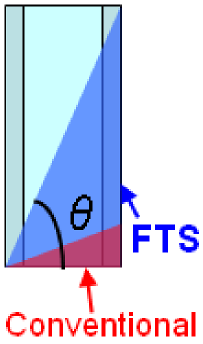
Data-MC for the impact parameter of tracks from $\nu_\mu CC$ interactions

Improvements On The Background Rejection

Large angle track detection

Undetected soft and large angle muons are the source of charm background
Detection of particles and nuclear fragments in hadronic interactions

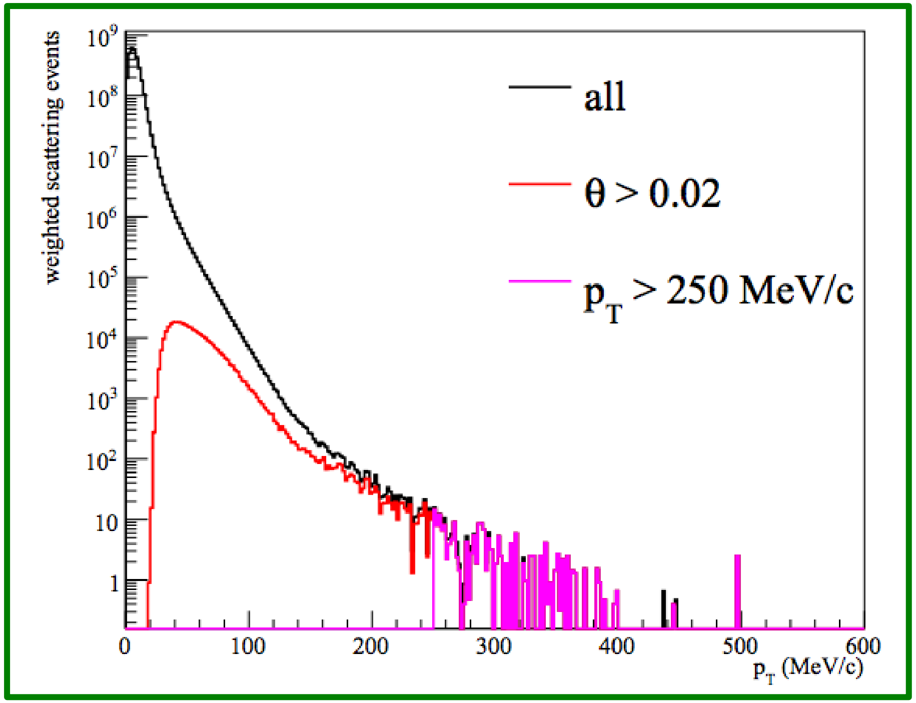




JINST 9 (2014) P12017

Large angle μ scattering

CNGS ν_μ CC muons on Lead $1 < p_\mu < 15$ GeV/c



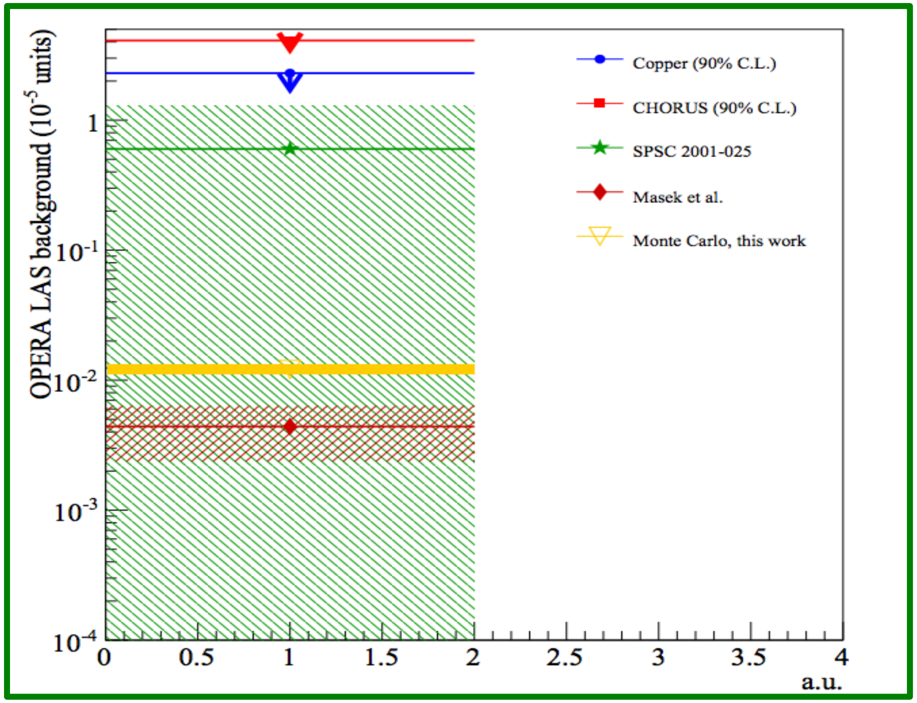
Main background in the $\tau \rightarrow \mu$ decay channel when using upper limits in the past

LAS background estimation

$$(1.2 \pm 0.1) \times 10^{-7} / \nu_\mu^{CC}$$

well below the values considered so far

IEEE Transactions on Nuclear Science

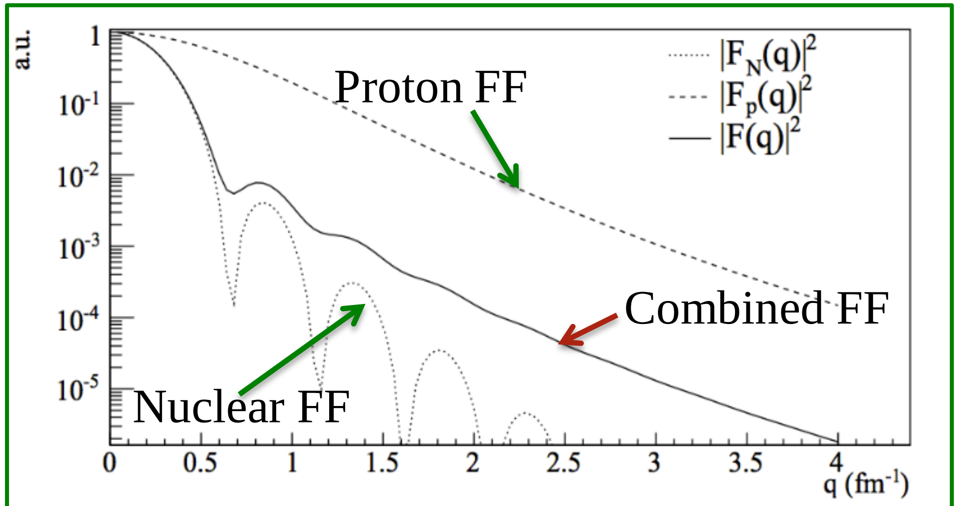


Large angle μ scattering

New estimate based on GEANT4
- Simulation modified by introducing form factors (FF) for Lead
(Saxon-Woods parameterization)

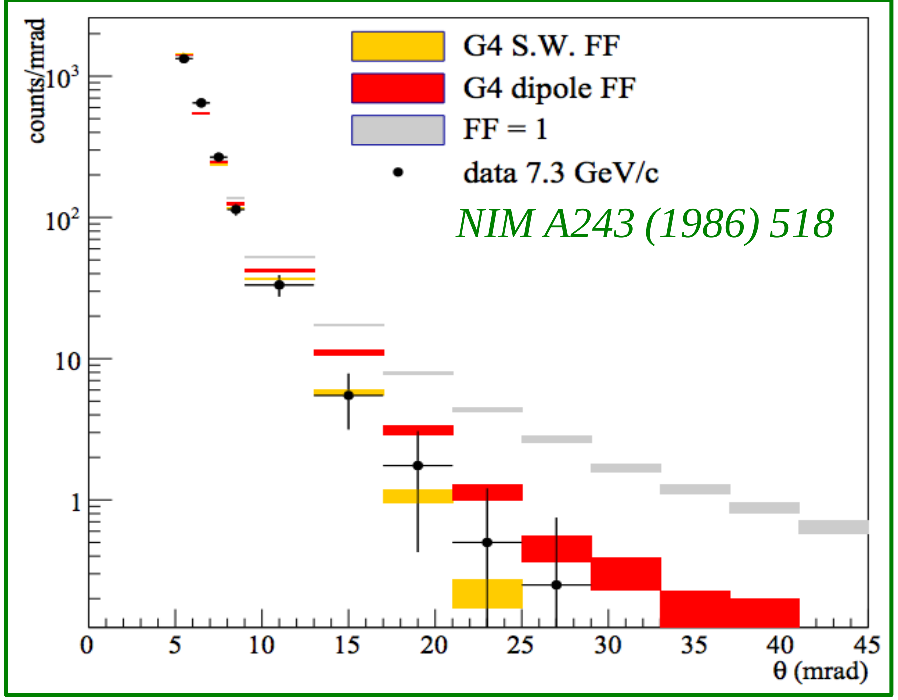
$$\rho_{SW}(r) = \rho_0 \left(1 + e^{\frac{r-b}{a}}\right)^{-1}$$

IEEE Transactions on Nuclear Science

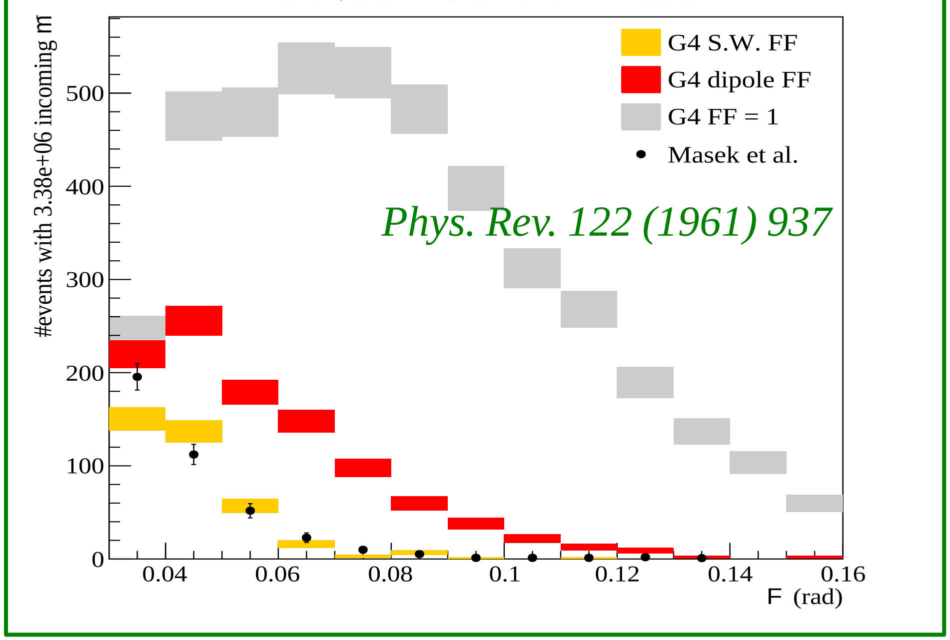


MC predictions compared to available data

7.3 GeV/c muons on Copper



2 GeV/c muons on Lead



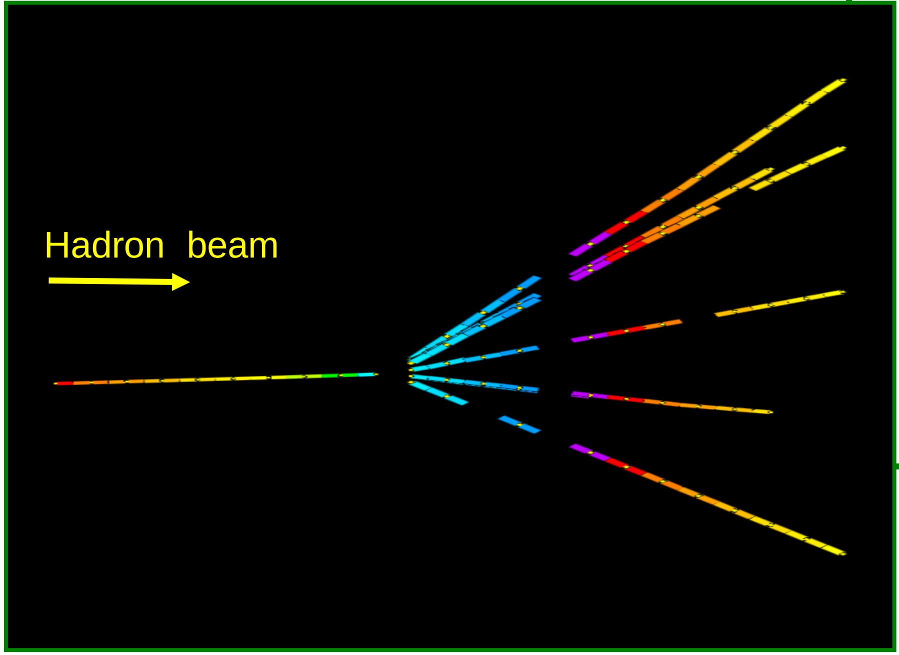
Background Studies: Hadronic Interactions

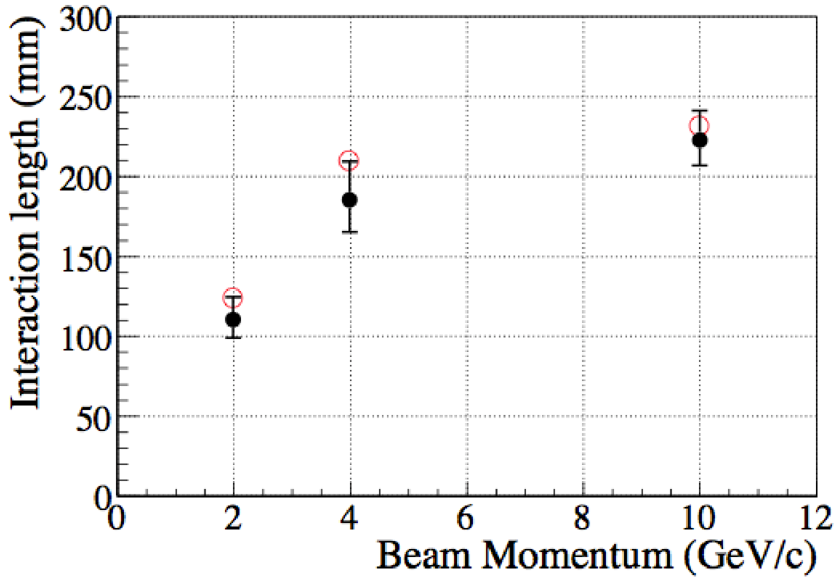
Comparison of large data sample (π^- beam test at CERN) with Fluka simulation

→ check the agreement and estimate the systematic uncertainty

Track length analysed in the brick:

- 2 GeV/c : 8.5 m
- 4 GeV/c : 12.6 m
- 10 GeV/c : 38.5 m



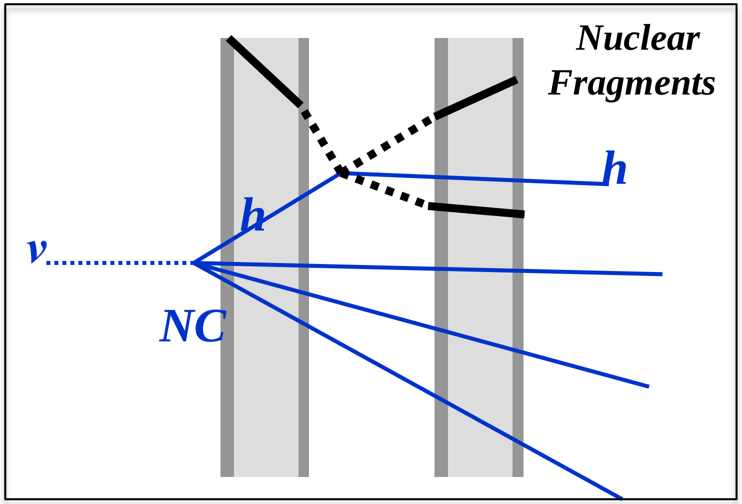


Black : π^- beam data

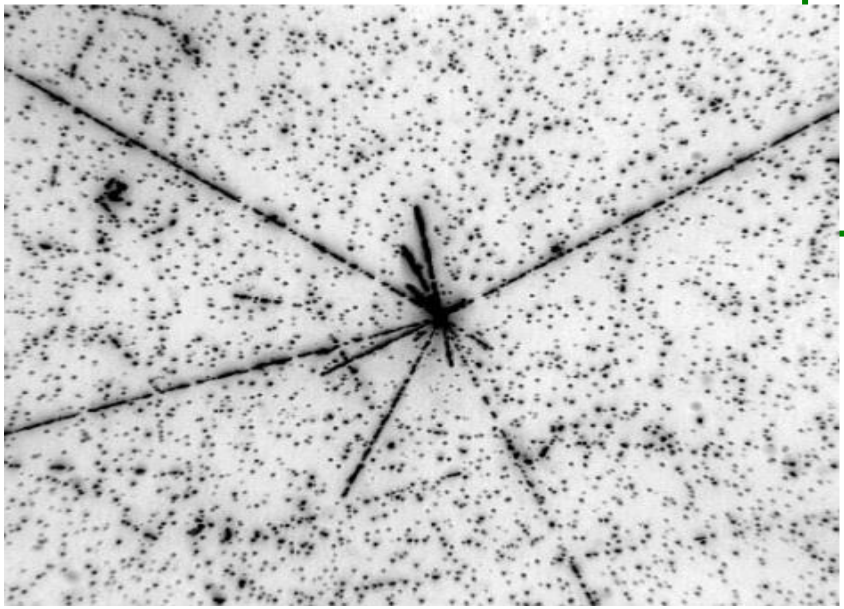
Red : MC (FLUKA) simulation

PTEP 9 (2014) 093C01

Nuclear Fragments Emission Probability

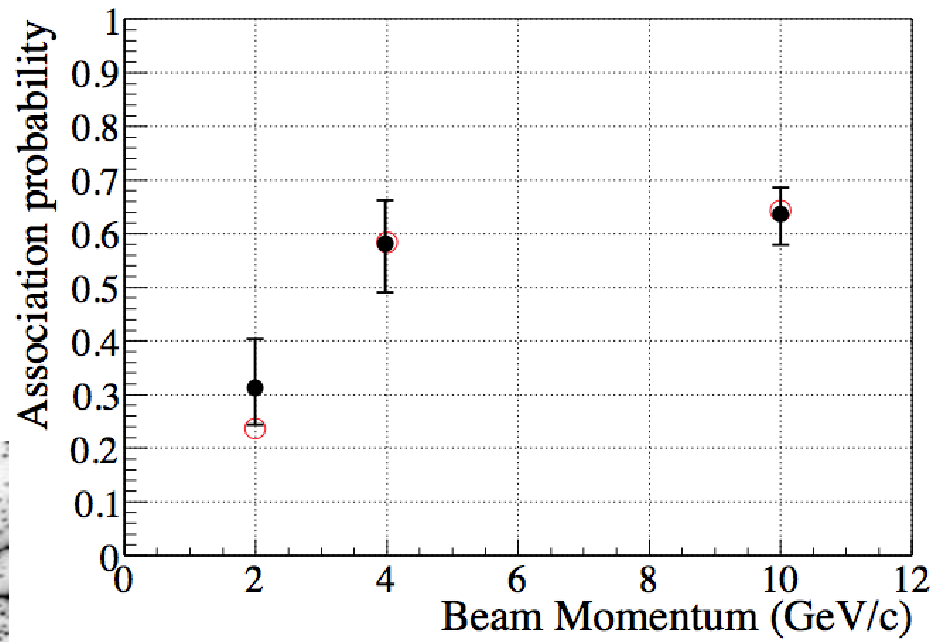


Highly ionizing fragments



150 µm

Additional background reduction

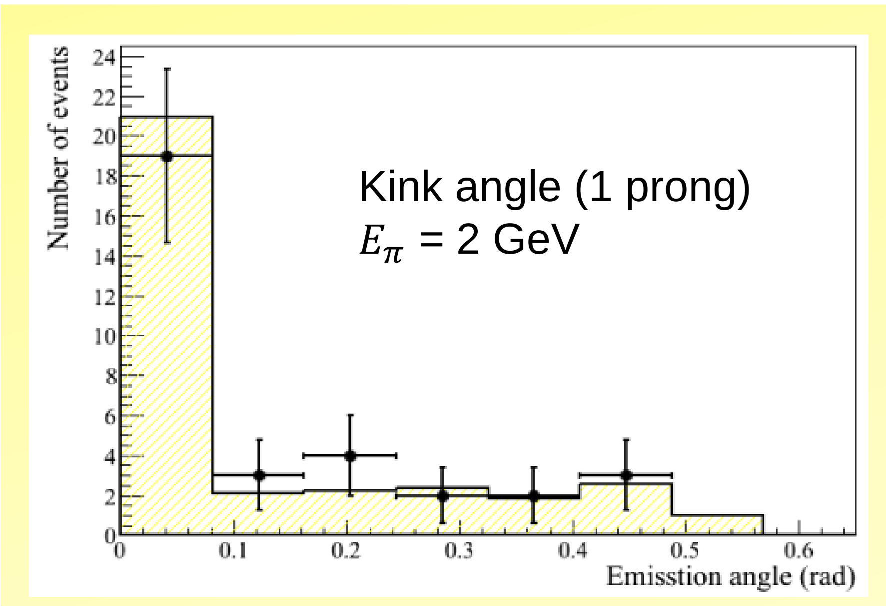


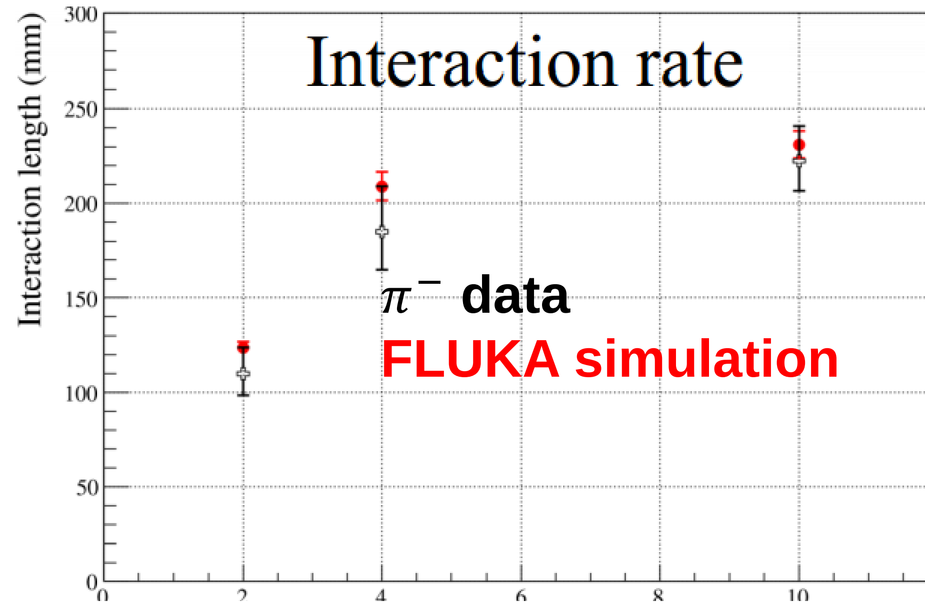
Black : experimental data
Red : simulated data (β= p/E = 0.7)

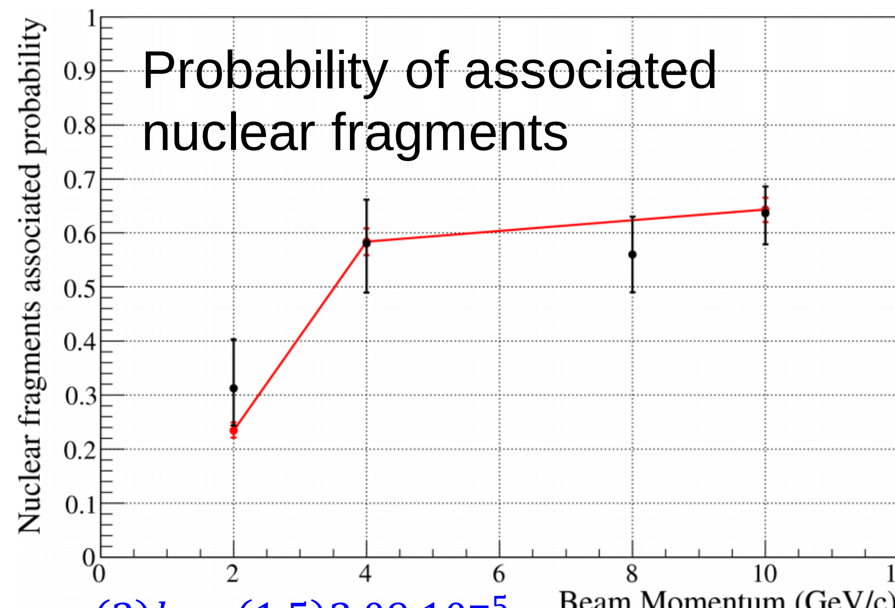
PTEP 9 (2014) 093C01

Hadronic background: π test beams

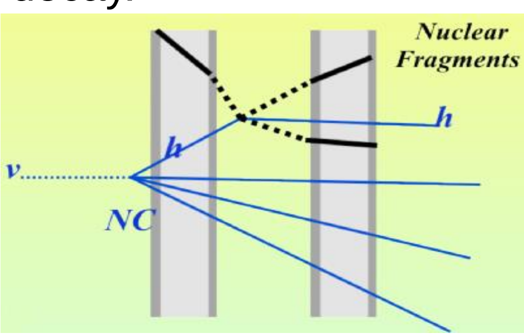
CERN π^- test beam

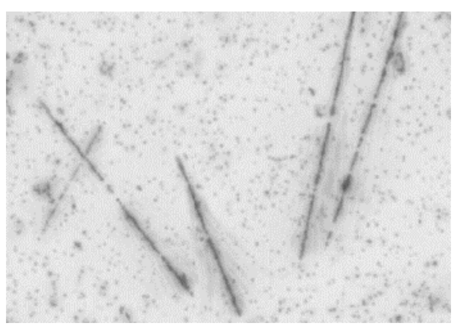






Nuclear fragments: a smoking gun for the occurrence of an π interaction instead of a decay.





Hadronic background rate per located event: $\tau \rightarrow (3)h = (1.5)3.09\ 10^{-5}$